THE POTENTIAL OF BUILDING-INTEGRATED PHOTOVOLTAIC SYSTEMS IN ZIMBABWE AND THEIR APPLICATION TO THERMAL ENVIRONMENTAL CONTROL

EDMUND MUNYATI

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ABSTRACT

A strategy has been devised to assist the photovoltaic technology to evolve to the point where it should be a major player in the provision of sustainable energy supplies to loads that are in grid-connected locations in Zimbabwe. The strategy has been devised through an investigation carried out on grid-connected commercial-building loads. The objective of the research undertaken in this programme is to formulate a novel strategy of utilising the photovoltaic technology such that viable financial mechanisms which will provide the funding for the photovoltaic technology in the target area are stimulated.

Many financial mechanisms have been given global impetus but it has been generally acknowledged that the success of all renewable energy technologies is dependent on introducing them in such a manner that local finances are capable of funding them. This can only be achieved by persuading existing financial structures to accept these technologies by penetrating the market which these structures are used to dealing with. The financial structures can then be steered, from within, towards the target market. The strategy also builds on the successes achieved by international donor-funded projects in identifying the market potential of utilising photovoltaics as in the GEF PV projects, and the technical viability of the local industry to support the technology as in the GTZ PV projects. It establishes a new method of increasing the capacity of the photovoltaic systems in the region under consideration to a level where it would set a trend that can accelerate the decrease in the cost of the photovoltaic technology in the local area.. This adds a fifth dimension to the four major directions being taken to reduce costs of photovoltaic systems, which are reducing the amount of solar materials used; reducing the amount of energy and labour used in processing; using alternative manufacturing equipment; and investigating novel solar materials.

The strategy proposed is based on the concept that optimising the performance of the energy generating system, optimising the efficiency of the system whose energy load is met by the power system and continually identifying market-efficient applications of the technology on which the power system is based is part and parcel of achieving a sustainable base for the long term utilisation of the technology. It shows the best way of removing the negative view that is widely held that excluding applying the state-of the-art of a technology in the major markets of photovoltaics, the developing countries, is the only viable way of achieving development. It also lays the basis for the efficient introduction of smart energy-efficient appliances and novel solar devices such as transparent solar cells and AC modules as well as concentrator technology in future, when these concepts have progressed out of the laboratory.

In this project commercial buildings in a chosen benchmark city were used as the energy demanding load. Photovoltaic arrays integrated into the building facades were taken as the energy generating systems. The energy requirements of the air-conditioning plant in the buildings were taken as the parameter for which various control paradigms were investigated in order to achieve the optimum method of utilising energy generated by photovoltaic systems installed on the buildings. The resources used in this investigation included hourly weather data obtained from the benchmark city and building data from the city scape. Generic and transient building energy simulation computer software tools, TRNSYS and DOE2 respectively, were used to estimate the energy utilisation of the buildings and to test the various control paradigms formulated. A solar resource estimation software program was developed inhouse to estimate the available solar energy incident on the various surfaces of the buildings, and a control system simulation program, MATLAB Simulink, was used to test the performance of the proposed mounting system for the photovoltaic modules.

The project focused on utilising the building integrated suntracking photovoltaic arrays as shading systems. It used a recursive parameter estimation method to predict the reference for controlling the position of the photovoltaic arrays and enable them to fulfil the dual purpose of generating electricity for the building and reducing the air-conditioning load by reducing the solar gains into the buildings through providing the shade for the windows. It also investigated the effect of utilising energy conservation measures such as designing buildings for natural ventilation and thermal massing. Finally an estimation of the reduction of the cost of air-conditioning system on one of the building due to shading was made so that the effect of this reduction on the cost of funding the installation of building-integrated PV can be investigated.

It was generally concluded from this work that: i) utilising building integrated photovoltaic systems in the target market could lead to a significant contribution to its energy supply; ii) there were convincing reasons why using building integrated photovoltaic systems was a reasonable way to proceed in promoting the technology in the target area because the building market was the only market in the country which had the capital to adopt the systems in a commercial mode, and thus stimulate the interest of the local financial structures; iii) there is need to optimise the load in these buildings before photovoltaics can be effectively incorporated as the major source of energy iv) the acceptability of photovoltaics as the major source of energy differed among building types, but it was generally accepted that the more energy efficient buildings were the ones where photovoltaics could be the main if not the only source of energy; v) an integrated approach to future energy policies was the only way for a sustainable energy supply in the target market; vi) the strategy is applicable on a regional scale because of the geo-economical location of the benchmark city.

This project investigated the technical viability of the building-integrated of photovoltaic systems in Zimbabwe. Further research on the topic requires demonstration systems of the proposed plants, and an in-depth economic analysis can be made from these.

Dedication

This thesis is dedicated to all members of the teaching profession whom I have had the honour of being a student of, especially my parents, Faith and Gilson Munyati whose role went beyond the call of duty.

ASPIRATIONS AND VISION FOR DEVELOPMENT

Although this research was aimed at on-grid locations, the target market was a developing country which has a majority of its energy consumers in terms of population in off-grid locations. It is therefore my aspiration that the work carried out in the research will ultimately help both the on-grid and the off-grid locations in Zimbabwe by facilitating sustainable access to funds to people in off-grid locations. It is also hoped that by establishing a firm market in a capital intensive and professional on-grid market, this can guarantee the quality of the PV systems that will filter down to off-grid customers.

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List of Symbols

α is the altitude of the sun

β is the inclination of the surface receiving solar energy

β_T is the temperature coefficient of the module at maximum power

β_{vp} is the temperature coefficient for the maximum power voltage

Γ = angle of incidence

δ is the angle of declination of the sun

ϕ is the latitude of the location where the solar receiver is located

γ_s is the azimuth angle

ω is the hour angle

η_{tot} is the total photovoltaic system efficiency

η_{array} is the efficiency of the photovoltaic array

η_{inv}, is the inverter efficiency

θ_Z is the zenith angle

ρ_g is the ground reflectance

Γ is the compound angle between the sun line and the array normal

A_a is the photovoltaic array area

A_c is the solar cell area,

A is a curve fitting constant in the solar cell

a parameter specific to a material used in equation linking temperature to band gap voltage (0.0007eVK^{-1} in silicon)

ALCC annualised life cycle cost

b parameters specific to a material used in equation linking temperature to band gap voltage (1100K in silicon)

C_{clad} cost of conventional cladding system

C_{pv}.. cost of PV module

C_w cost of wiring

C_{inv} cost of inverter

C_{panel} cost of passive panel to be replaced by PV

C_{pwp} cost per watt peak of solar modules

η_{mod} solar conversion efficiency of modules

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m number of parallel strings in a module

n the number of cells in series in a string

n_{bw} is the intra-module wiring loss factor

n_d the diode factor

n_{fw} the wiring loss factor

n_{mm} is the mismatch factor for series connected modules

N_t the total number of solar cells in the array,

P_{dc}, the DC power produced by the array

P'_o is the undegraded solar module output at normal incidence at one solar constant, and at reference temperature 25°C.

P_{mo} the power output of the module at standard conditions

Pa(n) annualisation factor

q the electronic charge, 1.602×10^{-19} C

R_s shunt resistance

T_a ambient temperature

T_c cell temperature under prevailing conditions

T_0 is the reference cell temperature, usually 25°C

T_r cell reference temperature, 25°C

V_c cell voltage

V_D - diode voltage drop

V_{oc} open circuit cell voltage

V_W wiring voltage drop,

v the ratio of the voltage across the load to the open circuit cell voltage

V_B - array bus voltage

V_{mp}, the output voltage of the module at its maximum power point and under standard operating temperature and intensity

ΔV_s is the change in maximum power voltage due to change in irradiance from the standard one.

Chapter 1

Introduction

1.1 Energy and Development in Developing Countries

1.1.1 The Effect of Sources of Energy

In developing countries, the rate of growth of the economy almost always outstrips the rate at which energy supplies are acquired[1]. Their energy infrastructure needs increase rapidly with population growth, urbanisation and economic development. More often than not they rely on imported finite sources of energy. These sources such as coal, oil, natural gas and nuclear material are obtained from static and bound stores like fossils and minerals, which can only be transformed into usable forms by extensive and highly skilled human activity. This means that when developing countries import these energy sources they have to pay for the actual fuel, the transport cost and the labour. Moreover, the danger posed by radioactive materials released by nuclear fuels make them not attractive globally, and particularly so in the developing countries where the delicate management required for this technology can be difficult to facilitate. Moreover, the proliferation of nuclear arms to these countries become easier if this technology is promoted in them[3].

This can be contrasted with the second class of energy sources, the renewable energy sources, consisting mainly of solar, wind and water. These are infinite because they are due to continuous and repetitive energy currents in the environment taking place all the time. They can also be found in nature in a form which can be readily introduced into electricity generators, as shown in Figure 1. At least one of these resources, solar energy, is available in abundance in developing countries, especially those in the sunbelt between latitude 40°S and 40°N, which are also some of the poorest. Table 1 compares the characteristics of renewable energy sources and clearly shows that solar energy is one of the few sources available world-wide [2].

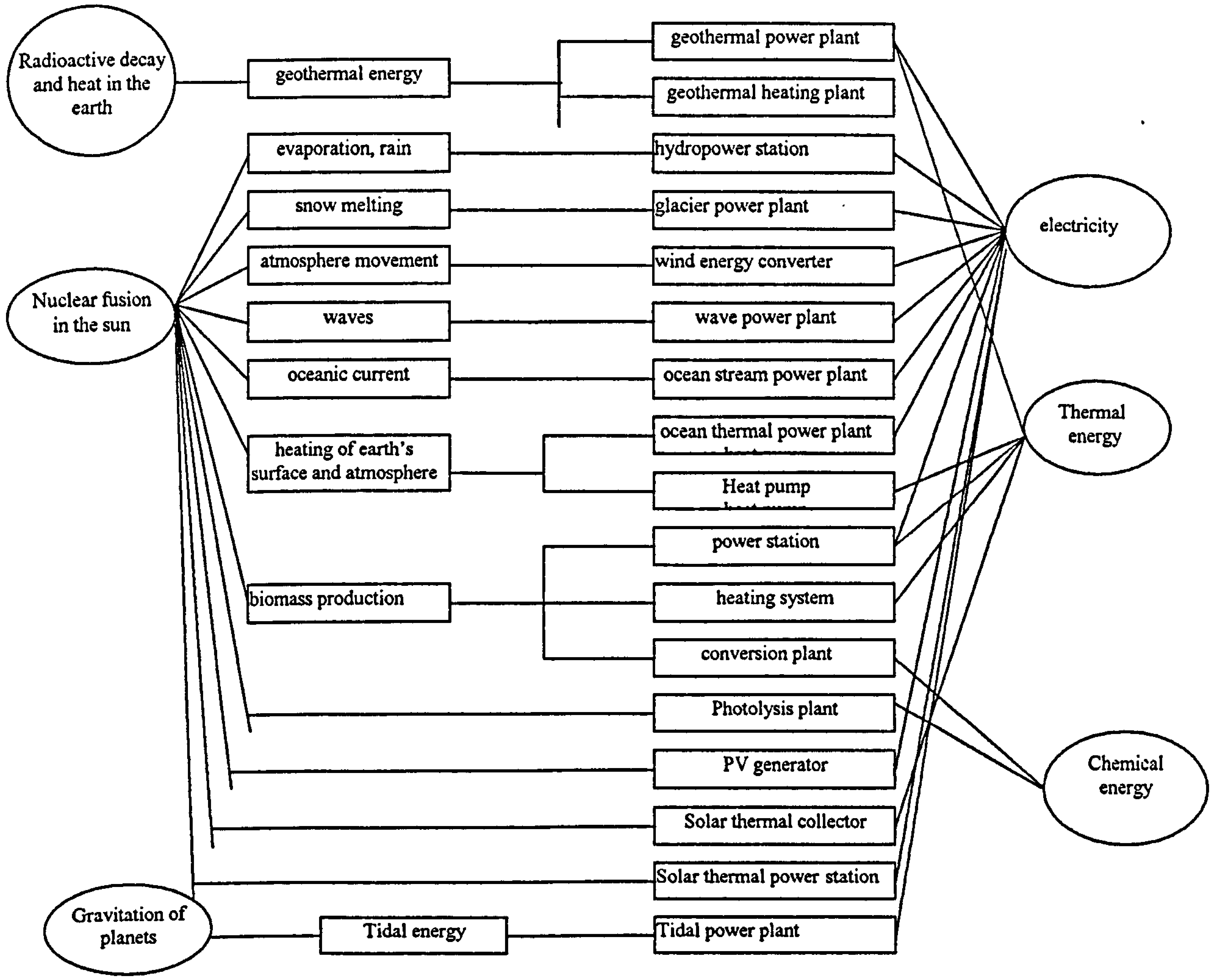

Figure 1.1: Possible Technical Conversions of Renewable Energy Sources

Resource	Magnitude	Distribution	Variation	Intensity
Solar Energy	Extremely large	World-wide	Weather Dependent	low(1kW/m^2 peak)
Wind Energy	Large	Coasts, Mountains Plains, Offshore	Highly Variable	Low average(0.8MW/km^2)
Water Energy	Large	Mountains	Seasonal	Moderate to low
Wave Energy	Large	Coasts	Variable	Low
Ocean Thermal	Very Large	Tropics coasts	Seasonal	Low
Biomass	Very Large	World -wide	Climate Dependent	Moderate to Low
Geothermal	Very Large	Tectonic Boundaries	Constant	Low Average(up to 600°C)
Tidal Energy	Large	Coasts	Tidal	Low

Table 1.1: General Characteristics of Renewable Energy Sources

1.1.2 Energy Infrastructure Considerations

Historically, global industrialisation has been propelled by fossil fuels, with the industrial revolution in Western Europe and America being a case in point. This has lured developing countries into following this learning curve. The evidence however is that their development has been constrained by the lack of a sufficient energy infrastructure. An effective energy system contributes to economical development by increasing productivity, establishing new industries and diversifying the economy. Therefore, access to affordable energy is essential to sustaining the socio-economic development strategy of a country. However, meeting the energy needs of a large population involves mobilisation of considerable sums of capital for investment in the energy infrastructure. The sources of capital for such large scale investment have become more competitive and scarce. Even though, the energy sector has continued to receive substantial attention from governments, donors and development agencies because of its central importance.

1.1.3 Environmental Considerations

The by-products of utilising fossil fuels such as oxides of carbon, sulphur and hydrocarbons pollute the atmosphere and have recently been found to have adverse effect on the ozone layer and consequently on the climate[3]. Developing countries have therefore been caught up in a time warp, where they have found themselves struggling to deal with the negative environmental effects of the conventional sources of energy before the energy produced by these sources has had as much impact on their development as it did in Europe. Indeed fossil fuel energy generating technology has seen vast improvements in industrialised countries, while most developing countries are still using the old polluting generating technology. These fuels will continue to dominate the energy supplies of developing countries, especially those who have extensive reserves of the raw materials[4]. However, it remains a fact that a radical change in energy policy is required. An energy source which is sustainable and an energy policy in which the developing countries can be at the frontiers of the generating technology is the only way these countries can have their development accelerated by the available energy supplies. Renewable energy technologies, best suit such an energy policy. Photovoltaics, in particular, is one of the few technologies where the manufacturing base and the installation capacity can be made locally available in the country of use, even if it is a developing country. Ambitious strategies therefore need to be devised to ensure that such a policy can be viably implemented.

1.1.4 Rural Area Power Supply

There also exists another dimension to the energy problems of developing countries, especially those in Sub-Saharan Africa. This is that the majority (over 70%) of their populations live in the rural areas. These people make use of wood as their main source of energy for cooking, and use candles and kerosene for lighting[5]. These sources of energy pollute the environment through production of carbon dioxide(CO_2) and carbon monoxide(CO). CO_2 influences the climate through the green house effect which has been said to be causing global warming. Moreover firewood is becoming increasing scarce and in some cases villagers, usually women have to travel miles to fetch it. This also creates a vicious cycle whereby as the wood resources become depleted the disruption of the hydrological cycle results in limited water supplies. The consequence of this is that a further need for energy to tap water from deeper reserves arises. This, coupled with the already existing need to have cleaner water raises the energy requirements of the rural community considerably. It is therefore imperative that alternative sources of energy are found for the benefit of the rural area based part of these populations. In most developing countries extending the grid has not been considered because the urban areas themselves are not fully electrified.

The little electrification that has been done is through using diesel generators and photovoltaic systems, both of which are too expensive for the average rural area person.. There has therefore been a tendency to label photovoltaics as an expensive small power range source of energy for a poor market, the rural population. It is somehow correct to assume that it is a power source for the rural areas because, they can easily be decentralised and sized according to demand. The belief that it is too expensive has become a stigma, whereby this energy source has not been included in national energy policies. Photovoltaics can however be included in the generating mix because they are equally capable of generating megawatts of electricity. They also have the added advantage that they can generate electricity at the point of use, and they allow gradual growth because they consist of modular units which can be added onto each other with time. In those countries were photovoltaics is appreciated, the lack of funds within the intended market has hampered development to the point that only donor assisted projects have been significant. Methods of sourcing local funds are therefore required.

PV power systems are best suited as the alternative energy source to conventional systems because of their low maintenance requirements, low pollution and the long life of the power generating panels (20 to 30 years) [6]. However, their high initial cost has been the biggest limitation to their application, especially in developing countries[2]. Consequently, they have been confined to low power applications like PV-powered water pumping systems and stand alone roof mounted systems on domestic dwellings where they can only supply power to audio-visual appliances and lighting. Even then, the implementation of these systems have been such that in countries which have a high market potential (developing countries) their commercial viability has been difficult to justify.

1.1.5 Commercial Building Energy

The globalisation of the world economy has meant that a country can have a viable economy only if it can attract foreign investors. In developing countries the ability to provide the necessary working environment for a high profile business community has been one of the biggest challenges. This community usually occupies high rise commercial building offices in the central business districts of the country's major cities. This tendency has been exported to developing countries with mixed success. The earlier building designs were not energy conservative, and full mechanical air-conditioning systems were used to attain comfort levels. Though modern architecture allows buildings without mechanical air-conditioning in certain climates, the corporate statement that goes with the fully air-conditioned buildings still sells and fully air-conditioned buildings continue to be built.

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for such a concept and the failures previously experienced due to an unknown technology being introduced suddenly on a developing world market are avoided. There are many developments associated with this technology to which a future market should become acquainted as they happen, so that it can be in a good position to pick the best options. One key area is the welcome prerequisite demanded by the concept of building integrated PV systems. This is that the building design should be energy efficient at first before any energy resource can be called upon to fulfil its comfort requirements .

1.2 Energy Background of Zimbabwe

1.2.1 Energy and Economy in Zimbabwe

The energy sector in Zimbabwe accounts for 8-9% of gross domestic product(GDP), but contributes only 1% of formal employment. It also has a larger share in aggregate investment, foreign borrowing and debt. Investment in it totalled an equivalent of Z$2 billion between 1980 and 1989. This was about 12% of Gross Domestic Capital Formation. 75% of this energy investment was in electricity. Zimbabwe is 84% self-sufficient in energy requirements, but has to import all petroleum products. This cost US$210 million in 1989 and accounted for about 13% of the energy supplies. The finance for energy has mostly been supported through debt rather than retained earnings as net financial savings in the public sector are generally negative. The energy sector debt is increasing considerably[12]. It reached Z$874 million dollars in 1989, which was 10.5% of the year's GDP. The external electricity related debt alone was Z$583 million or 6.2% of GDP. In 1990, Zimbabwe's energy imports were valued at Z$583million, which was 11% of foreign exchange earnings, while liquid fuel imports have steadily increased annually as shown in Table 2.

In 1994 the total electricity imports had a value of about Z$297 million, it was Z$296million in 1995 and was expected to be Z$506million in 1996 due to the installations of regional interconnectors to South Africa and Mozambique. The capital and foreign exchange intensive nature of the energy sector tends to strongly influence economic policy decisions. The implications of the energy debt has been severely felt because foreign exchange rate has been the binding constraint to economic growth.

Fiscal Year	Cost/Z$million
1990/91	748.8
1991/92	945.5
1992/93	1,295
1993/94	1,320
1994/95	1,573
1995/96	1,840

Table 1.2. Annual increase in liquid fuel imports

1.2.2 Sources of Energy in Zimbabwe

Zimbabwe's major energy sources are coal, hydropower, biomass and the sun.

1.2.2a. Coal

The estimated coal reserves are 11 billion metric tonnes of which 2 billion can be extracted by open cast mining. The coal is mined subject to licensing and conformation to environmental standards[12]. A private company Wankie Colliery Company is responsible for the main production and distribution of coal. 60% of its output is thermal coal, and this is jointly produced with high grade coal. Another private company, Sencol, produces high grade coal. Other private companies play supportive roles in the distribution of the coal, but the transport capacity is provided by the National Railways of Zimbabwe, and the Ministry of Mines supervises the mining policies as well as making the pricing decisions. Coal is currently priced on a cost-plus basis, with periodic reviews. Its importance to power generation means its price has a direct effect on the cost of electricity. The pricing is such that the national utility which buys the coal for thermal production of electricity does not prefer to import electricity instead. It has been observed that the production of thermal coal and high grade coal make setting an appropriate price for it difficult.

1.2.2b. Water

The Zambezi River on the northern border has an estimated hydroelectric potential of 37 TWh per annum, of which 10TWh have been harnessed. The Zambezi River Authority , jointly owned by the Zambian and Zimbabwean governments, is responsible for maintaining existing and future dams on this river. There are other inland rivers, with potential for mini and micro-hydroelectric plants, such as the Mwenezi and Manyuchi rivers on whose confluence a dam was constructed. A mini-hydroelectric plant with an exploitable power potential of 170kW and capable of providing 1,700kWh per annum electrical energy has been proposed for this dam.

1.2.2c. Biomass

Fuelwood covers 20% of the land area . This represents a stock of 320million metric tonnes, with a sustainable yield of 13 million tonnes[13]. The total national fuelwood consumption rates is estimated at 8 million tonnes per annum . This means the national fuelwood needs should be able to be met.

1.2.2d Wind

Wind potential has been reported in some literature to be negligible except for water pumping. There are however few areas where the yearly mean speeds have been identified as high. The wind speed for the weather stations shown in Map A.2 in Appendix A are shown in Table A.1 of the same appendix.

1.2.2e. Other

Ethanol from sugar cane has been used to blend imported petrol, but the desired 20% level of blending has not been met because of recent droughts. Instead 13% has been used.. Coal bed methane is also available, but not yet exploited. However, plans are being made for a gas field producing 182,500 ft^3 of methane per day, with a 15 year potential. The area represents only 5% of the total potential.

1.2.3 Energy Consumption in Zimbabwe

1.2.3a. Biomass

Wood for fuel and agricultural residue constitutes 52% of total energy consumption in the country [Table 5], and provides basic energy services to 80% of the rural population. It is also a source of power to some of the high density urban areas. It has been mentioned above that the available wood resources in the country should meet the national demand. However there are localised shortages in numerous districts. In fact it has been reported that 27 out the 57 districts are in a deficit situation as far as fuelwood is concerned[13]. There is also little trade of fuelwood surplus to areas with deficits due to low trading margins.

1.2.3b. Coal

Although it exists in abundance in the country, it only contributes only 13% of the total energy consumption as follows i) power generation (2.91 million tonnes), industry (0,609 million tonnes), agriculture (0.362 million tonnes), mining (0.052 tonnes). The difficulty in pricing it due to production of a mixture of thermal and high grade coal makes it difficult to trade as a household commodity. Transport costs are also high. The fuel switching of the coal needs to be enhanced by upgrading the coal, but the technology may not be economical.

1.2.3c. Liquid Fuels

These contribute 16.6% of the total energy consumption. The fact that these are all imported has led to innovative measures to be sought to alleviate the cost burden. These include using ethanol as a fuel extender; looking at mode substitution in transport such as rail electrification; increasing the energy efficiency of road vehicles and searching for oil reserves in the country.

1.2.3d Electricity

Overall electricity consumption is 11.8% of total energy consumption. The consumption of electricity by each sector of the economy from 1993 to 1995 is shown in Table 3

Sector of The Economy	Electricity Consumed/GWh	
	1993/94 Fiscal Year	1994/95 Fiscal Year
Agriculture	752	903
Commerce	1,040	1,383
Industry	3,107	3,507
Mining	1,166	1,571
Residential	2,209	1,658

Table 1.3: Energy Consumption by Economic Sector[14, 15]

Zimbabwe, like most developing countries, has the majority (over 70%) of its population living in the rural areas. These people, also make use of firewood for cooking and use candles for lighting. The overall rate of electrification in the urban areas was estimated to be 72% in 1992. It was estimated to be only 5% in the rural areas.

1.2.4 Electricity from Conventional Sources in Zimbabwe

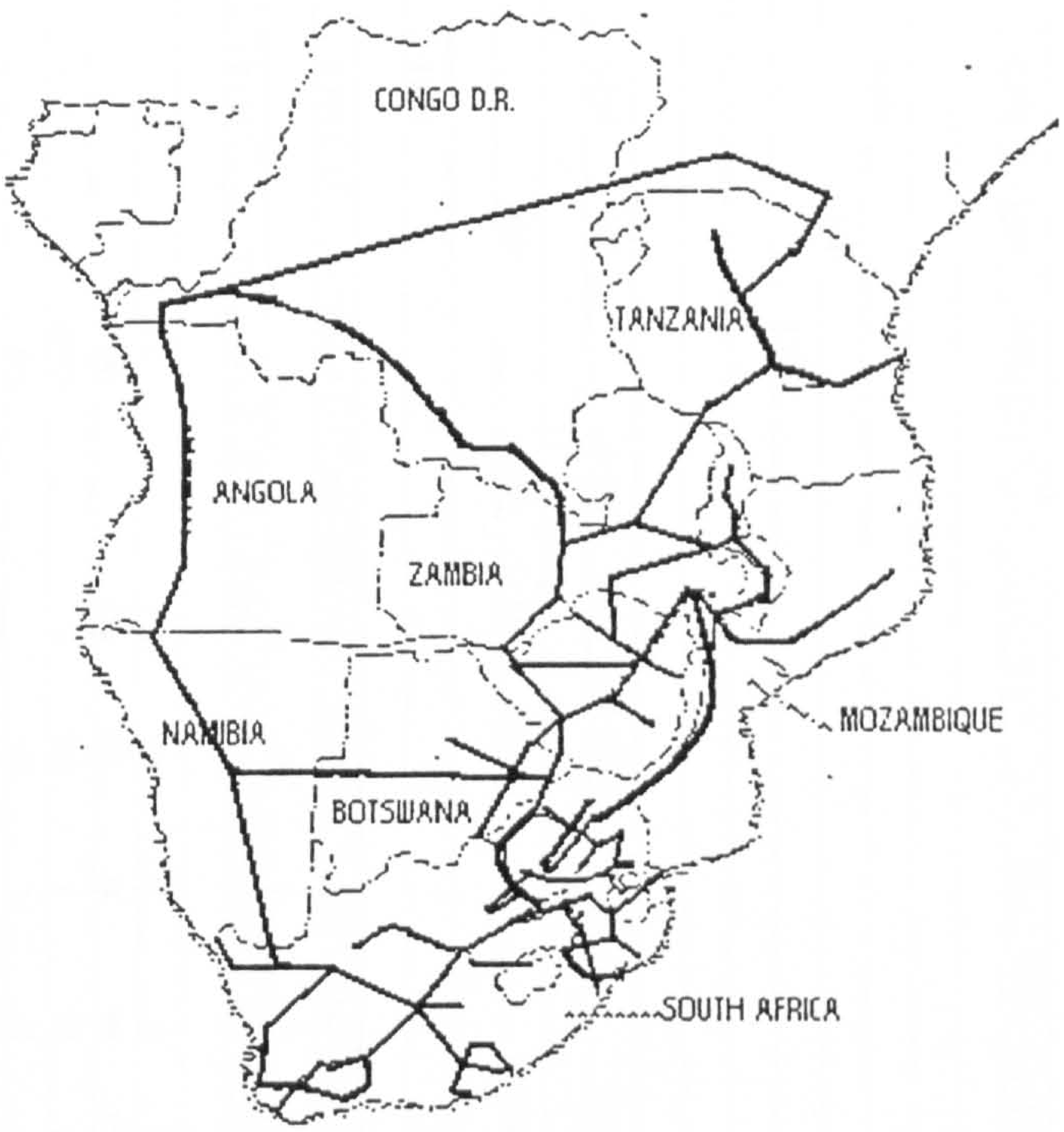
1.2.4a Zimbabwe Electricity Supplies

The Zimbabwe national grid is the responsibility of the Zimbabwe Electricity Supply Authority(ZESA) which has the mandate to ensure that there is adequate electrical energy to meet the nation's power requirements at an affordable price[17]. In the past ZESA had to do this through the operation of its two major power stations: Hwange Thermal Station with an installed capacity of 924 MW and Kariba South Hydro-Power Station with an installed capacity of 666 MW , as well as old thermal power plants at Munyati (120 MW), Harare(135 MW) and Bulawayo (120 MW). The Bulawayo station has now been retired. It has also had to import power from Zaire and Zambia. Electricity imports accounted for 20% of the total final electricity consumption in 1993. Increased development in different sectors of the economy of Zimbabwe has meant that there has been an increased demand for electrical energy which has made it necessary for ZESA to make a massive investment increase its capacity. These include imports of power from South Africa and Mozambique. There are also plans for the future extensions to the Hwange Power Station(500MW) and Kariba Power Station(300MW); for the upgrade of the Kariba Station(84MW) and for the future construction of the Batoka hydro-power station(800MW) and Sengwa thermal station(1.100MW(net)) [18]. The power available and expected in future to it are shown in Table 6 which shows the net capacity balance in the fiscal years 1996 through 2015. ZESA being a member of the Southern Africa Power Pool (SAPP) [Table 7] is required to have 19% planning reserve margin for thermal utility and 10% for hydro utility, while that for a mixed generation is a weighted average of the two. The figures in Table 6 show that it should have sufficient capacity to meet the projected peak demand and the 20% reserve margin through fiscal year 1999 using existing capacity and imports. After that it would require additional capacity which by 2015 will have reached 2,628MW. The extensions and refurbishments mentioned above would cost US$4 billion including the cost of the power plants, transmission/distribution lines and substations.

1.2.4b Rural Electrification

Prior to 1980, the history of rural electrification in Zimbabwe was characterised by supplying electric power to commercial farms only. The inhabitants of communal areas were ignored and this had extensive adverse effects on economic growth in these areas. This left the present government with no choice, but to find ways of electrifying these areas. Extending the grid to cover the rural areas was initially considered [19]. In the 1980s the national utility managed to connect 36 rural service centres out of a total of 562. The power consumption at each of these centres was less than 100kW and an average number of only 10 households were connected at each centre. Rural electrification through grid extension was suspended in 1987 due to lack of funds. This is hardly surprising because international experience with extending the grid to rural areas has shown that the high and increasing cost of investment in the power sector has contributed to the debt burden of the developing countries[20] The consumption rates in rural areas are often very low and the dispersed nature of the rural area residents(about 20 people per square kilometre in Zimbabwe) poses transmission difficulties. This means that the supply of electricity will not be economical because the operating costs are not covered by the revenue, capital repayments have to be subsidised and maintenance could suffer. The rural electrification of Zimbabwe was resumed in 1989 with a review of the rural electrification masterplan[21]. The consultants involved still advocated grid extension as the best way for rural electrification, and they ruled out independent power supply sources such as renewable energies. They however acknowledged that this can only be successful if rural electrification can be treated as a social programme supported by public funds, and that the low load factor in the rural areas need to be improved by promoting load growth through development. The masterplan also had recommendations which meant that the rural population supplied with electricity would increase by 30% to about 207,000. This would have left in excess of 5 million people unlikely to be supplied with electricity by the national power authority in the foreseeable future[22].

Figure 1.2. Transmission Line Network of SAPP



1994 ZIMBABWE ENERGY BALANCE

IN TERAJOULES (TJ)

	Coal	Coke	Breeze	Coal tar	Coke gas	Ethanol	Diesel	Petrol	Jet A1	Paraffin	Avgas	LPG	Blend	LFO	Electricity	Woodfuel	Charcoal	Molasses	TOTAL ENERGY
PRIMARY SUPPLY	146 101	-6 831	-1 653	-540		435	30 020	13 172	6 429	600	161	287			16 013	138 783	23		342 999
Production	146 165					485									8 651	138 783	201		294 186
Imports	1 132	723					32 986	13 172	5 243		194	287			7 462				61 199
Exports	-1 712	-4 450															-183		-6 345
Stock Changes	516	-3 104	-1 653	-540		-51	-2 966		1 186	600	-33						4		-6 041
TRANSFORMATION	-93 889	14 764	1 653	1 647	4 668	-106	-4 003								21 231	-720			-51 863
Charcoal																-720			-720
Coke & by products	-21 642	14 756	1 653	1 647	4 568														982
Ethanol						-106													-106
Hwange power station	-62 799						-3 995								19 355				-47 440
Old Municipal power station	-9 448						-7								1 791				-7 664
Private power station															84				84
ENERGY SECTOR	-16 042				-1 827	-329		-12 506	-2 650	2 650			12 836		-8 462				-23 331
Transfer						-329		-12 506	-2 650	2 650			12 835						.
Own Consumption															468				468
Losses	-15 042				-1 827										-8 930				-23 799
FINAL SUPPLY	37 171	7 926	-0	1 108	2 741		26 017	668	3 779	3 260	181	287	12 835		30 782	138 062	23		264 805
% difference	-4	0		0			0		-0	0	4	-4	5		0	0	-0		-0
FINAL CONSUMPTION	38 848	7 926		1 108	2 741		25 974		3 779	3 245	151	299	12 273		30 782	138 057	23		264 906
Agriculture	17 212						3 043		0	109	5	6	231		3 138	7 865			31 606
Commerce & services	1 267						8 484		564	799	10	65	1 564		4 650		8		15 413
Industry	16 809	7 887		1 108	2 741		2 237		2	338	0	161	290		11 906		7		43 373
Mining	1 857	2					870			15	0	12	81		5 018		8		7 683
Residential	301									1 877		81			6 790	130 192			138 221
Transport	1 302	37					13 640		3 213	108.4	130	8	10 103		191				28 831
Road							11 829			104.8		3	10 052						21 988
Rail	1 302	37					1 660			0.7		1	32		191				3 233
Air							43		3 212	2.9	130	1	19						3 408

Notes:
LFO and Molasses omitted because calorific values not known
Zero indicates less than 0.5
Calorific value for blend has been used although there was very little ethanol

Table 1.4: Zimbabwe Energy Balance 1994 [16]

Net Capacity Balance
(Fiscal Year)

	1996 (MW)	1997 (MW)	1998 (MW)	1999 (MW)	2000 (MW)	2001 (MW)	2002 (MW)	2003 (MW)	2004 (MW)	2005 (MW)	2006 (MW)	2007 (MW)	2008 (MW)	2009 (MW)	2010 (MW)	2011 (MW)	2012 (MW)	2013 (MW)	2014 (MW)	2015 (MW)
Thermal																				
Hwange 1	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114
Hwange 2	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114
Hwange 3	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114
Hwange 4	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114
Hwange 5(1)	180	196	196	196	196	196	196	196	196	196	196	196	196	196	196	196	196	196	196	196
Hwange 6(1)	180	196	196	196	196	196	196	196	196	196	196	196	196	196	196	196	196	196	196	196
Harare 2 6	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
Harare 3 1	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27
Harare 3 2	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27
Munyati 3	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
Munyati 5	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
Bulawayo 1(2)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bulawayo 2(2)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bulawayo 3(2)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bulawayo 4(2)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Thermal	924	955	955	955	955	955	955	955	955	955	955	955	955	955	955	955	955	955	955	955
Hydro																				
Kariba South(3)	666	666	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750
Total Generation	1,590	1,621	1,705	1,705	1,705	1,705	1,705	1,705	1,705	1,705	1,705	1,705	1,705	1,705	1,705	1,705	1,705	1,705	1,705	1,705
Imports																				
Zaire	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Zambia	200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Matimba	300	150	150	150	150	150	150	150	150	0	0	0	0	0	0	0	0	0	0	0
Cahora Bassa	0	500	500	500	500	500	500	500	500	0	0	0	0	0	0	0	0	0	0	0
Total Capacity	2,190	2,271	2,355	2,355	2,355	2,355	2,355	2,355	2,355	1,705	1,705	1,705	1,705	1,705	1,705	1,705	1,705	1,705	1,705	1,705
Total Demand	1,756	1,838	1,923	2,011	2,102	2,187	2,271	2,354	2,439	2,528	2,620	2,715	2,813	2,916	3,021	3,131	3,245	3,363	3,485	3,611
Reserves Requirement	231	238	255	272	290	307	324	341	358	506	524	543	563	583	604	626	649	673	697	722
Capacity Requirement	1,987	2,076	2,178	2,283	2,392	2,494	2,595	2,695	2,797	3,034	3,144	3,258	3,376	3,499	3,625	3,757	3,894	4,036	4,182	4,333
Surplus/(Deficit)	203	195	177	72	(37)	(139)	(240)	(340)	(442)	(1,329)	(1,439)	(1,553)	(1,671)	(1,794)	(1,920)	(2,052)	(2,189)	(2,331)	(2,477)	(2,628)

1. Capacity increase at Hwange 5 & 6 due to completion of upgrade works.
2. The Bulawayo units are to be retired in June of 1995. They have been listed because, as of the date of this study, they represent 45 MW of installed generation.
3. Capacity increase at Kariba South due to refurbishments.

Table 1.5: Net Capacity Balance Electricity in Zimbabwe

1.2.5 Zimbabwe National Energy Policy

The constraints in the energy sector relate to:-

i. Low capacity in the electricity sector

ii. Insufficient grid coverage, especially in the rural areas

iii. Insufficient reticulation in the urban areas

iv. High transport cost for coal

v. High transport cost for fuelwood

vi. High capital cost for solar systems

The objectives of the energy policy are to find the solutions to the problems in the context of a global market economy and the economic restructuring environment that exists in the country. They therefore include:-

i. Ensuring accelerated economic development

ii. Facilitating rural development

iii. Promoting small to medium scale enterprises

iv. Ensuring the development of environmentally friendly energy

v. Ensuring the efficient utilisation of the available energy resources

These objectives were established with the full knowledge that Zimbabwe is a signatory and a beneficiary of Agenda 21 adopted at the United Nations Conference on Environment and Development, 1992 [23]. It also holds the presidency of the World Solar Commission. The energy policy therefore focuses on the following strategies:

i. Limiting energy demand to an extent consistent with maintaining growth through pricing based on economic costs and efficient energy use. This requires the available energy resources to be exploited in such a way as to optimise energy production and consumption, and to minimise the negative effects on the environment. Therefore, the non-renewable resources are to be used at a rate consistent with long-term national needs and goals and renewable resources to be exploited at sustainable levels.

ii. Choosing an appropriate level of reliability of supply.

   The reliability of supply must balance the need for adequate energy supplies while minimising their cost. This allows resources to be made available for investment in other sectors of the economy. The actual reliability achieved depends mainly on risks which cannot be controlled, but which resolve themselves over time. Thus, subsectoral planning targets such as the 60 days supply capacity of liquid fuels, and the 20% limit on electricity imports have to be reviewed to fit circumstances.

iii. Utilising opportunities for regional co-operation in energy.

Where it is more economical and more reliable to utilise regional supply options instead of national alternatives the national policy gives provision for such a strategy to be adopted. This is subject to political consideration, and depends on the direct benefits to neighbouring countries of Zimbabwean energy imports, such as stabilising their economies, improving their security and increasing their export capacity.

iv. Enhancing rural development through provision of adequate forms of energy.

The energy policy states that growth should be promoted in the rural areas through provision of electricity, coal and renewable energy sources as energy substitutes to the scarce firewood. This is also expected to arrest the environmental degradation caused by deforestation.

v. Adopting an integrated approach to energy planning.

This is expected to fully integrate the energy sector in the economy and the economic development policy. The integrated approach is an effective planning tool, which enables early co-ordination between the targets of different sectors of the economy, and thus facilitates consistency in energy policy decisions, especially on investment and pricing.

vi. Adopting balanced energy management

This involves ruling out meeting unfettered energy demand, particularly electricity, since this has been found to stifle investment in other sectors of the economy. It is therefore expected that future energy demands will be kept within the limits consistent with economic growth by improving the energy efficiency and correct pricing at all levels.

1.2.6 National Energy Efficiency Programmes

The need for energy efficiency in Zimbabwe, in line with the national energy policy, has resulted in a number of programmes aimed at promoting energy efficiency being set up .

1.2.6a Zimbabwe Energy Efficiency Project(ZEEP)[24]

In 1992 the Department of Energy(DOE) and the International Energy Initiative(IEI), an international non-governmental organisation, initiated the development and implementation of a comprehensive electrical efficiency programme called the Zimbabwe Energy Efficiency Project(ZEEP). They used initial funds from the Rockefeller Foundation, USA to prepare tasks related to the development and demonstration of energy efficient projects in the industrial and commercial sectors of Zimbabwe. Energy audits were therefore carried out at 3 sites, one of them being a commercial building. However, demonstration projects were not implemented for financial reasons. One participant, the proprietor of the commercial building, turned down funds from the Rockefeller Foundation which had a 19% interest rate, because this was considered too high.

1.2.6b National Energy Efficiency Integrated Programme(NEEIP)[7]

This is an umbrella strategic framework that was developed to assist in: i) mitigating short-term energy supply problems and price rises; ii) coordinating energy efficiency at a national level as an integral part of an overall energy strategy and national economic development plan; iii)ensuring that energy efficiency provides sustainable development and reduces environmental degradation; iv) providing equitable distribution of energy resources; v) providing energy security and increasing competitiveness. It was expected to cover the following sectors: i) industry and mining ,ii) transport and agriculture, iii) commercial and iv) domestic. Its activities were to include, among other things, promoting energy efficiencies of appliances and promoting research and development activities in energy efficiency such as demonstrations, technical testing of products and use of existing programmes. The suitable implementing agency for such a programme was found to be the Energy Institute of the Scientific and Industrial Research and Development Centre

(SIRDC). The Energy Institute, and other participating local bodies would have been assisted by an advisory international agency such as ETSU who participated in the setting up of the framework.

1.2.6c National Energy Efficiency Conservation Programme(NEECP)[25]

This was initiated by the Zimbabwean Government's Ministry of Energy and Transport, the African Development Bank and the German Technical Agency (GTZ) with the intention of implementing an energy efficiency and conservation programme. It was set up with the long term objective of ensuring that the utilisation of energy is not only efficient but that the resources are exploited in an environmentally sound manner. It aims to redress the current situation where there is an imbalance between demand and supply of energy because the traditional energy planning focuses on the demand side only. It is unique in that it places reducing the adverse effects of energy production on the environment as a top priority alongside energy related economical competitiveness, deferred investment requirements in the energy sector and energy related savings in imports and foreign exchange. It focuses on industry and commerce because these are established business organisations who have defined functional guidelines and policies. They therefore are a good starting point for planning, implementing and evaluating energy efficient programmes, because financial mechanisms can be quickly worked out for them. They also represent growth in energy demand because they are the driving force of economic growth.

1.2.6d Conclusion

The events of the 1990s have steered Zimbabwe in the opposite direction to some of the recommendations of the Rural Electrification masterplan, especially the one that stated that grid extension should be the sole method to be used for rural electrification. This has the advantage that it gives rural electrification the chance to become commercially viable and therefore the ability to attract investment. This might not have been possible if it had been allowed to become a permanent social programme financed by public funds. It also removes the contradiction in the recommendation that a rural area can only be electrified if it has developed enough to have the right load factor, yet the electricity is needed for this development to occur. Moreover, this recommendation seemed to encourage more energy consumption beyond what the present needs warranted, which is totally against the principles of energy conservation. The need for energy efficiency and environmental conservation has brought renewable energy technologies into the national energy framework The Zimbabwe national energy policy and energy efficiency programmes clearly show that the policy makers subscribe to the view mentioned in section 1.1.3; that only an integrated, ambitious, but energy efficient and environmentally sound energy policy can provide the country with the sustainable energy supplies that it needs for rapid growth.

It is clear that what is required is a source of electricity that can provide a relatively small supply of power. Photovoltaic systems are undoubtedly the most suitable candidates for such an energy plan. However, it is a technology needing a high initial capital and, the financial structures need to be steered towards setting mechanisms that will make funds for renewable energy sources available at all strata of the society available

1.2.7 Commercial Building Energy in Zimbabwe

In Zimbabwe, the historical security in energy supply is increasingly being challenged by the rapid growth in the commercial building sector, coupled with the energy demands associated with the rate of growth of a developing country which almost always outstrips the supply. The city of Harare in particular has seen the construction of many new buildings in the last decade, and this has put a strain on the electricity supply. This has prompted the building owners to seek ways to minimise the use of electricity, because they are heavily penalised for excessive usage of it. This has led them to appreciate good energy management practices and use of alternative sources of energy such as solar water heating[26] and the use of thermal building massing[27]. Invariably where load shedding has to be applied the air-conditioning load has been sacrificed. It is within the context of the need to reduce the amount of electricity consumed in commercial buildings and the awareness that alternative energy technologies are a viable option on these buildings that innovative strategies of reducing the dependency on power supplied from the utility can be devised.

The city of Harare in is a fast growing city with high rise buildings being constructed at a fast rate. This has put a strain on the power demand from the national grid. The occurrence of acute droughts in recent times has meant that electrical energy shortages are inevitable. For instance, drought in the early 1990s meant that the output of Kariba Power Station had dropped in 1993 to half that of 1990 as shown in Table 6

Kariba Energy Output	
Year	Output/GWh
1989	3,196
1990	4,369
1991	3,152
1992	3,161
1993	2,062

Table 1.6: Kariba Hydropower Station Output

During that period building owners were made to pay heavy fines for exceeding their maximum demand. Concerns raised about the emission of greenhouse gases by coal fired power stations and the environmental degradation caused by the construction of large-scale hydropower stations gave impetus to the search for alternative energy sources[29]. This led to an energy awareness which made people acknowledge that renewable energy and energy efficiency activities are the only solution to Zimbabwe's future energy requirements not relying solely on ZESA's ability to increase supply with increased demand[30]. Initial research[31] has shown that energy efficiency programmes are required in the building sector in order to avoid the unnecessary and excessive energy consumption that is occurring in most commercial buildings in Zimbabwe. Other reports have indicated that about 41% of building power demand is taken up by air-conditioning.

This has led to a number of discussions among architects and building consultants. Indeed most institutional office buildings have no mechanical air-conditioning systems and some architects have argued that the Zimbabwean climate is such that they can design buildings without any air-conditioning requirements. On the other hand the building engineers have put this assertion to the test by designing the first passively ventilated office complex in Harare (Eastgate Office Complex)[27]. However, the trend is for tenant occupied buildings to be air-conditioned, so air-conditioning will continue to be a major consumer of power in Zimbabwean commercial buildings.

1.3 Context of This Research

Solving energy concerns in commercial buildings in Zimbabwe through reducing the dependency on conventional power from the utility and ensuring that energy conservation is carried out for the benefit of the environment requires controlling the air-conditioning loads and utilising an energy technology like photovoltaics which is environmentally friendly. After all, most of the old mechanical air-conditioning systems in use in commercial buildings utilise R11, R12 and R22 halogen refrigerants, which need to be phased out according to the Montreal Protocol because of their effect on the ozone layer [28]. This has retrofit implications and this could provide a chance for photovoltaics to be incorporated into the commercial buildings.

Historically, the high cost of PV systems meant they were confined to places where the utility grids did not reach[31]. These were mostly isolated domestic dwellings with system sizes of only a few kilowatts. However, the downward trend in the cost of PV, the need to use environmental friendly energy sources and the continued shortage of sustainable energy supplies has already resulted in research into the integration of PV in commercial buildings in the industrialised countries[32]. Moreover, matching of demand profiles with the PV supply has been reported to be much better for commercial purposes rather than for domestic purposes due to the operating schedules[33].

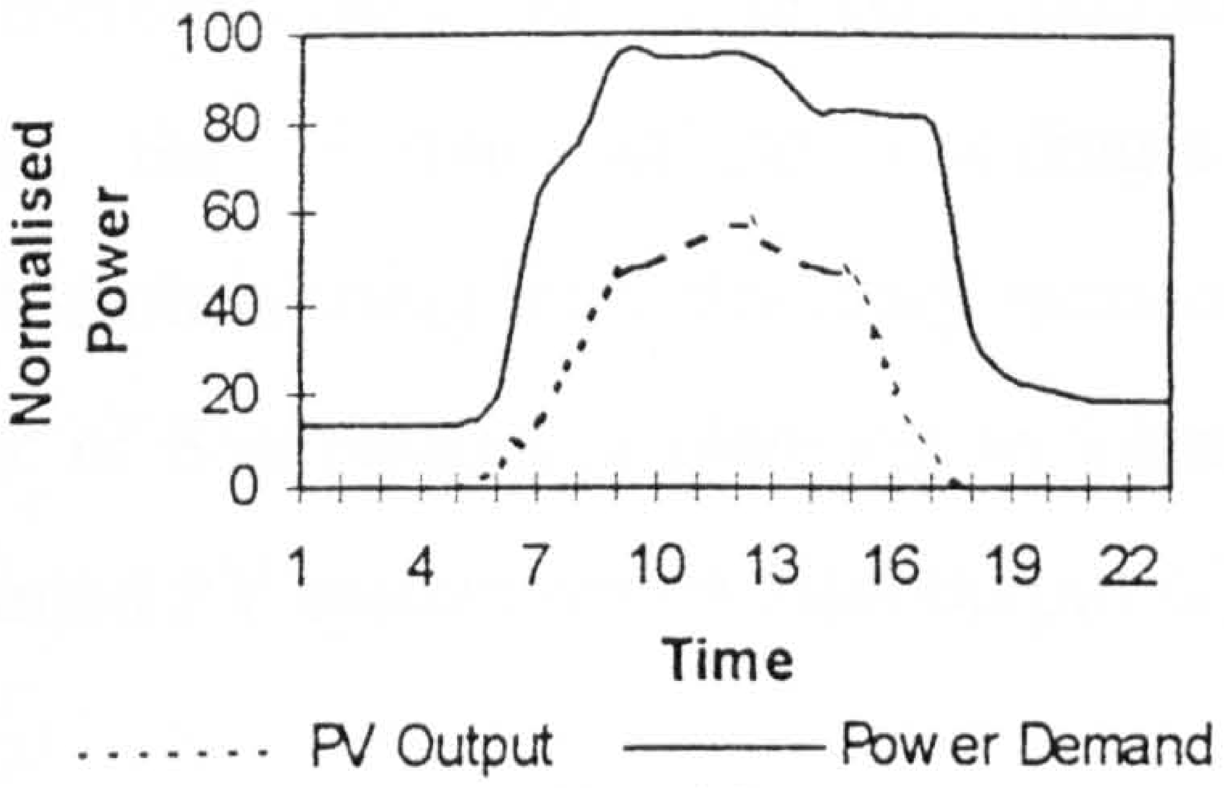


Figure 1.3a: Matching Commercial Building Demand and PV Supply

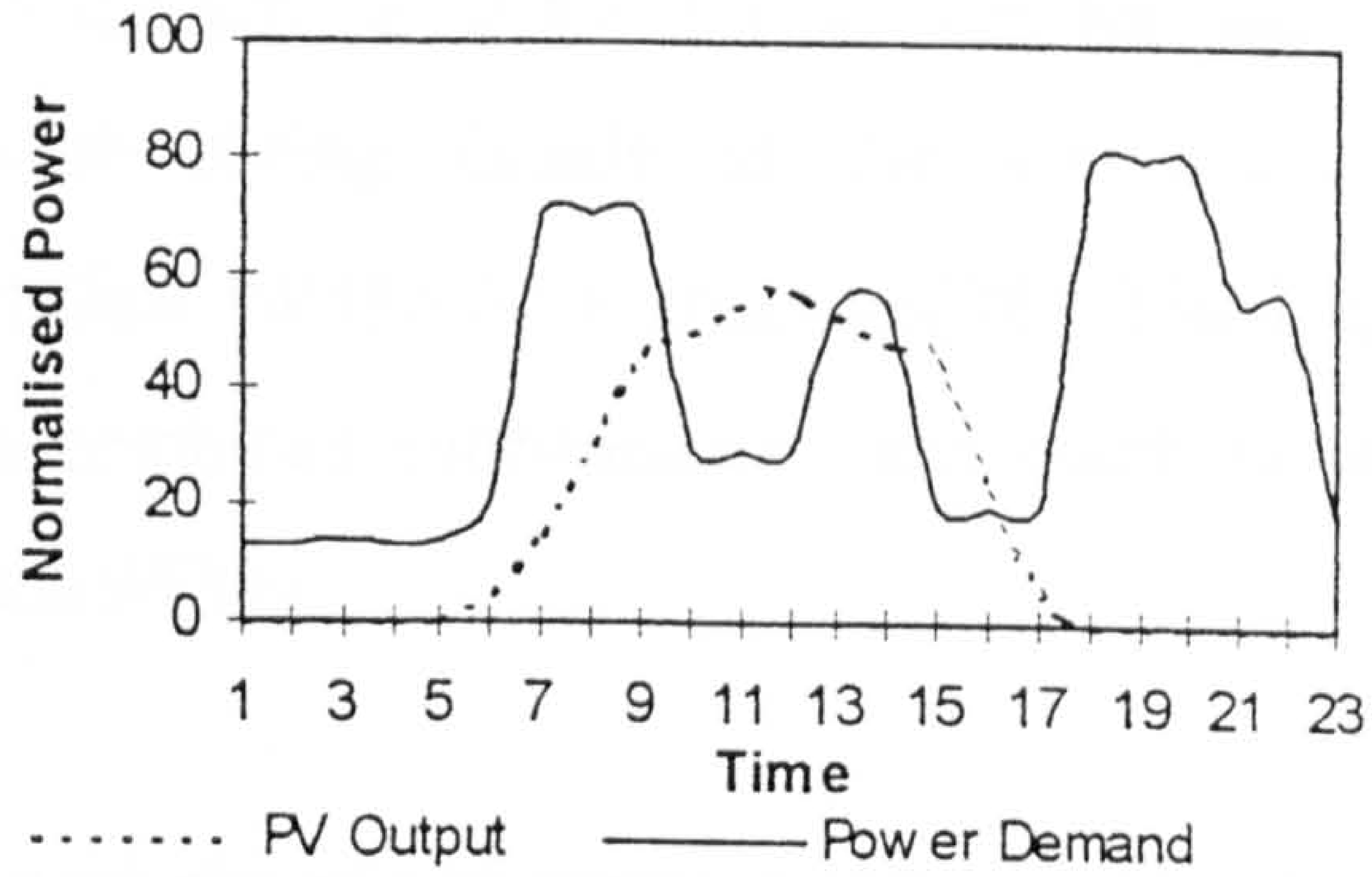


Figure 1.3b: Matching Domestic Demand with PV Supply

PV systems have therefore extended into areas with utility grids. The first step was the grid-connection of systems on houses[34].This concept was then extended to commercial buildings[35]. A number of demonstration projects have been set up and they have shown that the PV systems could contribute significantly to power demand. Initial estimates show that the systems are expected to be economical in the industrialised nations in the next 20 years[36]. The design of the existing building-integrated PV systems has been based on contributing to the total building energy requirements. All of them have, therefore, tended to be grid-connected. as they cannot supply the whole building on their own, because of the limited space available and the prohibitive cost.

The demonstration projects have been confined to northern latitudes [37]. In the United States in 1982 Solarex Corporation installed a 200kWp PV roof on its building, and in 1984 it installed the first commercial-scale building-integrated 300 kWp polycrystalline PV system on the roof of a building at Georgetown University, Washington D.C. In Japan Sanyo developed an a-Si module for commercial curtain wall applications. This semi-transparent module allows 30% transmission of light. It was installed on vertical facades of 3 office buildings in Japan alternating with opaque modules on non-view areas. In Germany, Deutsche Aerospace installed a vertical facade of a-Si modules and monocrystalline module suncontrol window overhangs on the Bavarian Environment Ministry office building. Phototronics SolarTechnik also developed 5 types of custom-made modules including opaque modules for cold facades, thermally insulated opaque modules, thermally insulated semi-transparent modules, thermally insulated hybrid PV/thermal panels and roof-tile modules. In the UK, a 40 kW PV system was used to reclad the Northumberland Building's south facing facade at the University of Northumbria using high efficiency monocrystalline BP585 Solar modules[38]. The Union Bank of Switzerland is planning to install a combined roof-mounted and south facade-mounted PV system with a total output of 200kW[39].

These systems have been known to aid in the peak shaving of power demand,[40] the better matchability between the building demand profile and the PV supply being attributed to air-conditioning loads[41]. Air-conditioning is more demanding in hotter climates and applications of PV in these places for refrigeration have been investigated[42]. However, as early as 1982 Naylor[43] proposed a PV air-conditioning scheme targeting refrigeration loads in Barbados and recently Pitts and Abbro[44] proposed a scheme of PV-assisted ventilation fans for buildings in Pakistan. Grocoff[45] investigated the effect of the building envelope and PV power as peak shaving tools in hot-arid climate residences. McCray[46] proposed a wholistic systems design approach incorporating space conditioning for remote houses in the USA. In the higher northern latitudes, full-scale stand-alone PV air-conditioning prototype tests have been carried out under the Joule Project[47] while at the University of Northumbria the extent to which the PV-cladding on the Northumberland Building can satisfy a hypothetical full air-conditioning load in cooler latitudes is being investigated [48]

McCray[46] has also reported that PV is better suited for integration into efficiently designed buildings. The PV system will then be able to take a substantial amount or all of the targeted electrical load. The energy efficient building should have a good design and also utilise other forms of renewable energy such as passive solar heating and daylighting. A number of energy efficient houses incorporating PV have been set up for demonstrating the possibility of self sufficiency in renewable energies[49, 50]. Commercial buildings can be made efficient with respect to the energy consumed by air-conditioning systems through control of their building structure's elements or control of the plant.

Building massing, which is the dynamic control of a building's energy consumption through the use of its potential thermal storage of the building mass, has been reported to decrease both energy use and electrical demand[51]. This is a more energy conserving control strategy than the conventional night setback control where the plant is turned off during unoccupied periods[52]. The bigger proportion of the internal gains are in the form of electromagnetic radiation which is absorbed directly by internal surfaces before being convected into the air space. With, typical thermal capacities of 20 to 40Wh/°C.m² it follows load requirements associated with maintaining comfort conditions within the given space can be significantly shifted through management of the building's thermal storage with relatively small temperature swings[53]. The same report states that the biggest opportunity for building massing exist in cooling systems because these are strongly tied to ambient conditions and are typically powered by electricity.
Excessive cooling loads are caused by high solar gains. It has been reported[54] that a reduction in window area and reduced window transmission of light can result in reduced cooling loads. This has to be balanced, however, with the savings that are lost due to reduced daylighting. Energy saving can also be achieved through the optimal control and selection of the refrigeration plant[55] and ventilating equipment[56]. Investigations into efficient building design with respect to these parameters is therefore beneficial to considerations of building-integrated PV systems.

The introduction of building-integrated PV systems demands an understanding of the various mounting options because they affect the solar energy collected and the performance of the PV modules. The modules generate and accumulate heat during their operation. This needs to be removed away from the modules to prevent its build up[57]. The orientation of the modules determine the amount of irradiation falling on them, but it is however restricted by the building architecture.

Posnasky[58] has reported that an extensive use of PV on commercial buildings is possible only if PV panels fulfil the functions and requirements of a conventional roof or facade.

Some of the buildings mentioned above have successfully demonstrated that this is possible[59].

Most commercial buildings have an outer skin which is distinct from the load bearing structure. This skin can be replaced in the event of damage, ageing or refurbishment which occurs every 20 to 30 years. The cladding of PV modules can act as an outer skin on wall surfaces that receive direct sunlight for many hours during the day. Various existing cladding types have bee investigated [60]. These include curtain walling, rainscreen cladding, external shading and profiled metal cladding . PV modules installed under these cladding systems have different performances. Assessments of the tilt and orientation of the modules, temperature effects and ventilation of the modules is ongoing. It has been found that in some cases PV modules can be integrated into some cladding systems such as curtain walls and shading systems without modification to their design.
PV modules can easily replace external shades which are usually fixed or adjustable horizontal or vertical external louvres. The louvres can be adjusted automatically to provide maximum shade, matching the angle of the sun. The electrical power for this operation which is necessary only when the sun is shining could be derived from the PV modules themselves. Shading of the modules in city centres is unavoidable and this could be a problem for tracking systems as shading would reduce the efficiency of the tracking system[61]. Shading of the modules may also cause damage to the modules due to the hot spot effect, if the cells within the modules are differentially shaded.

The PV system generates electricity at a rate determined by the solar irradiation that falls on the modules and the efficiency of conversion of the modules. The output depends on the orientation of the modules. Cladding is parallel with the wall, therefore if PV modules are to directly displace it they will be mounted vertically which is not the optimal orientation for low latitudes. In higher latitudes a vertical orientation would enhance the output in winter and reduce it in summer. The variation of the output during the day can also be modified depending on whether modules face north east for morning peaks or they face north west for afternoon peaks in Zimbabwe.

The complexity of installing the modules at an optimal orientation is compounded by the constraints imposed by the fixings and connections. A larger size of modules with dimensions identical to the existing cladding elements could be advantageous.

It has already been noted that that it would be advantageous for the generation profile of the PV cladding to match the building demand of electricity as closely as possible[62]. Otherwise, a storage system has to be incorporated because solar energy is variable in nature and although on average it is well matched to the timing of many peak loads, there is at best a high statistical correlation between PV array output and peak hourly loads. Many electricity rate structures have a demand charge based on the highest peak instantaneous or short-time based integrated power consumption. Therefore, for a grid connected system, even a short period of PV array power shortfall due to a passing cloud can substantially disadvantage the economic usefulness of a system without storage. Such a system has an element of uncertainty which can be removed only by having a suitable amount of storage which integrates the variable output of the PV array. The output can then be dispatched during periods of highest value allowing reliable control of the system output for a prescribed length of time and making "peak demand shaving" more reliable.

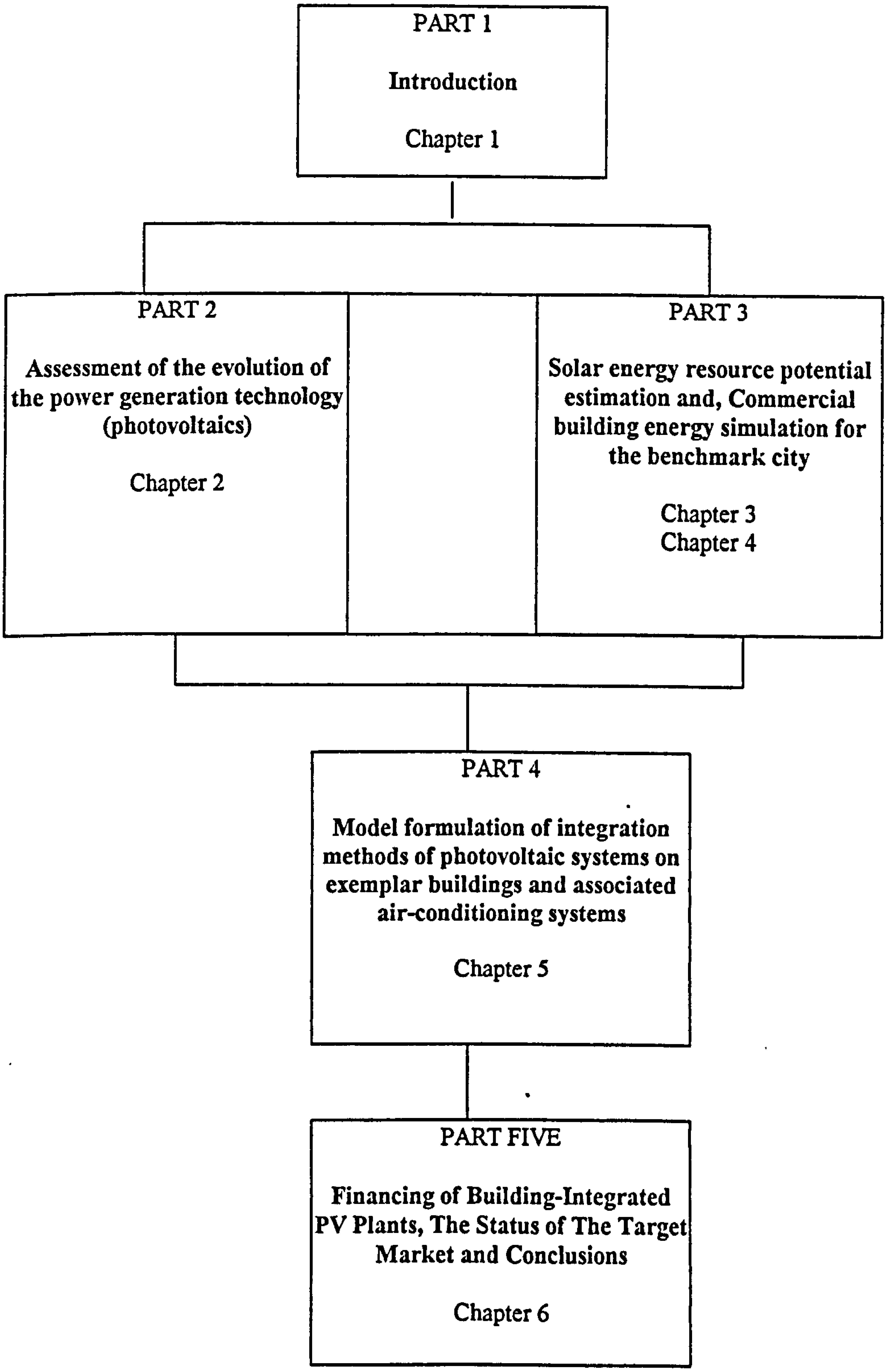
1.4 Aims Of The Project

This research aimed to consolidate the strategies set up within the national energy policy of Zimbabwe and its related energy efficiency programmes through investigating the idea of considering reducing air-conditioning energy loads as a way of enabling the efficient use of building-integrated PV systems on commercial-buildings in Zimbabwe. This research considered a holistic approach to the control systems of the plant, load and source of energy so that the reduced air-conditioning energy load could be powered by PV. It also sought to increase the volume flow of the PV technology in developing countries through targeting large scale local funding by the commercial(private) sector, instead of relying solely on external donors. A proposal of a building energy plan for Harare's commercial buildings incorporating

PV systems to assist in the thermal environmental control of the building was formulated through :

- carrying out topographical studies of a chosen benchmark city, Harare, the capital of city of Zimbabwe and categorising its building stock. Exemplars were then chosen for energy analysis and data was collected on the chosen buildings.
- choosing a generic energy simulation computer package to use as a vehicle for the energy analysis of the buildings and making a compatible weather file to be used for both the energy analysis as well as the PV system design considerations
- identifying the necessity of air-conditioning in the buildings in Harare by making energy models of the chosen buildings. This included investigation of the effects of varying building structure parameters through building massing, shading and fenestration.
- analysing the energy consumption of the existing air-conditioning systems that are claimed to be high energy users, through computer modelling and proposing ways to minimise their energy consumption.
- assessing the existing building-integrated PV technology through specific examples of commercial building-mounted PV systems in northern latitudes and their applicability to southern latitudes.
- identifying the different building energy loads that can be taken up by PV systems on buildings with either minimised air-conditioning systems or no air-conditioning at all.
- identifying the best way of installing PV systems on the buildings. Roof mounting is the best position for optimally collecting solar energy in Harare's latitude, but the roof to volume ratios limit the size of the roof-mounted systems. Therefore, an analysis of the existing building cladding systems was done so that the best alternative for mounting PV modules can be selected. A decision had to be made on whether the more sophisticated option of tracking can be used.
- considering the PV background in Zimbabwe, justifying the need for such a technology and proposing a plan for the efficient proliferation of the building-integrated PV technology in Zimbabwe

1.5 Organisation of The Thesis



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Chapter 2
State of The Art of Photovoltaic Technology

2.1 Evolution of Photovoltaic Power Generation

The most recent significant application of photovoltaic systems is building-integrated applications. To understand why this application has become important at this point in time and to fully appreciate the technological potential of photovoltaic power generation requires a good understanding of the present status of the technology and most importantly the trend the technology has taken since its conception. This assists in identifying future applications of the technology. Photovoltaic technology can therefore be taken as a technology undergoing rapid evolution.

2.1.1 Origins of Solar Cells

Photovoltaic power generation has evolved from 1839, when Edmund Becquerel discovered the photovoltaic effect[1] through 1877 when Adam and Day discovered a similar effect in solid selenium[2], with the latter finding important application in photography exposure meters after a 1% efficiency had been achieved in selenium and copper oxide solar cells in 1914. The development of the quantum theory of light and the progress in quantum mechanics and solid state physics [3] in the early part of this century led to the development of solid state p/n junction diodes and transistors [4] as well as operational solar cells in the 1940s and 1950s[5]. This progress led to the achievement of the significant efficiency of 6% for crystalline silicon solar cells in 1954[6] followed by the achievement of the same efficiency in Copper Sulfide/Cadmium Sulphide cells by Reynolds and co-workers [7]. After that period there was extensive research into improving the efficiencies of the solar cells as well as finding new materials for them. Consequently, there was rapid increases in cell efficiencies from that of the standard p-i-n cell of the 1960s, through the black cell of 1970s which achieved efficiencies of 17%[8] to the buried contact solar cells and the passivated emitter rear locally diffused cells of the 1990s which are achieving efficiencies in excess of 20% [9]

2.1.2 Market Growth

All technologies need a market to establish a niche which forms the basis for growth[10]. Solar cells found this in providing power for spacecraft, because the discovery of the significant cell efficiency above coincided with the birth of the space race. Thus in 1958, the first solar powered orbiting satellite was launched. This led to the establishment of solar cells as the primary source of power for satellites because they are light in weight and have high endurance. However, the space market was quickly saturated. Therefore, although this market was still significant, the PV technology had to find another market: the terrestrial market. This was assisted by the oil crisis of 1973 when the Middle East embargo made Western European countries and the United States seek self-sufficiency in energy. The United States government made block purchases of solar modules, and this stimulated the terrestrial market[11]. The stringent specifications for successive blocks guided the development of the industry

Photovoltaics was then expected to follow the success curve of microelectronics. However, the microelectronics technology had been allowed to grow gradually without facing stiff competition from established conventional technologies supplying the same market[12]. Consequently, while microelectronics grew through expanding markets which generated profits that financed continued development of the technology resulting in the ability to further expand into new markets, photovoltaics, on the other hand had to struggle against the unfair competition from conventional technologies [13]. It was, thus confined to a specialised market that could not generate the same profits to fuel the revolution required for the rapid development of large scale applications.

2.1.3 Technological drawbacks

The other drawback was that though microelectronics have the same technical requirements as PV in as far as the need for high quality materials, junctions and contacts are concerned, the requirements for solar cells are exceptionally demanding. These can be best understood by considering the standard n/p solar cell shown in Figure 2.1

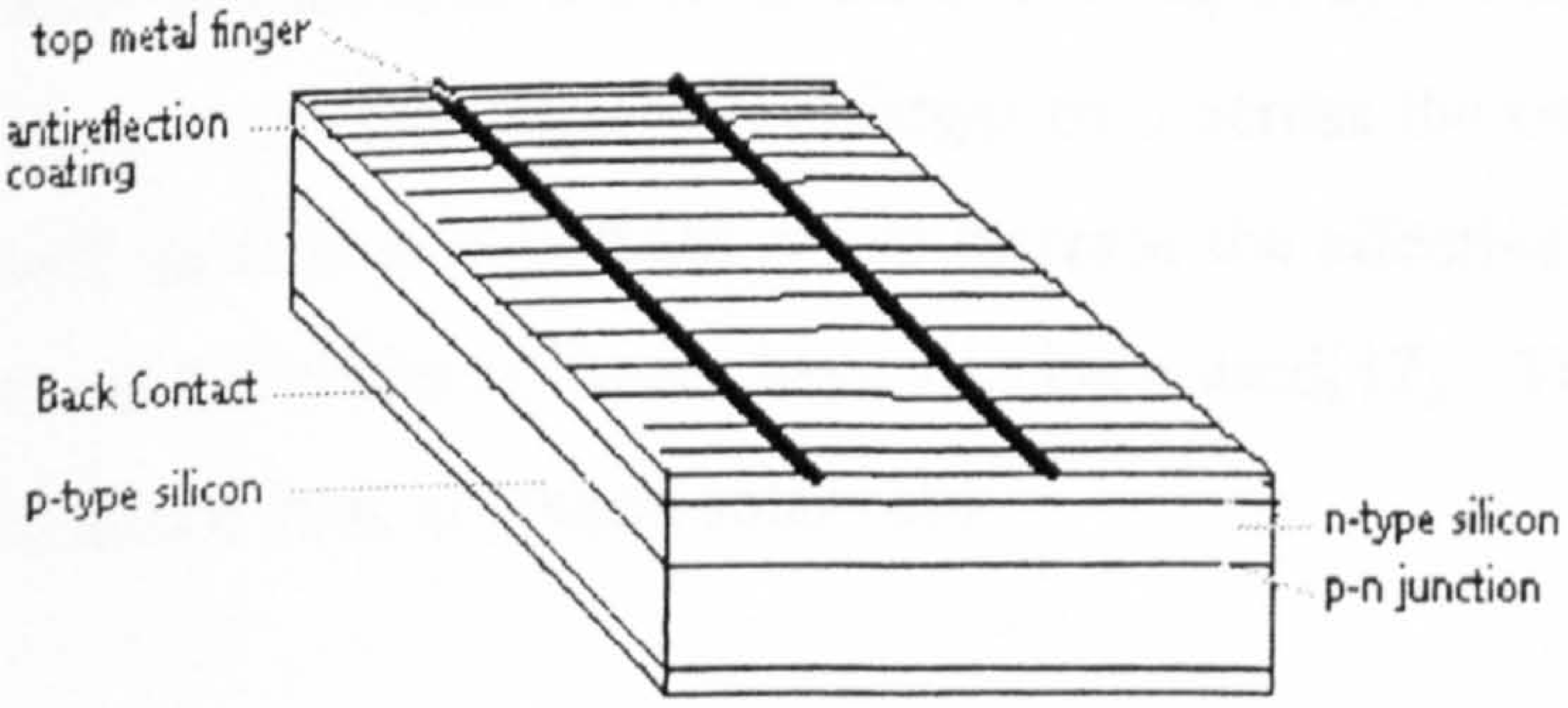

Figure 2.1: Standard n/p solar cell

The bulk and surface recombination must be suppressed to very low levels, ideal junctions are required, so are low contact resistances and high optical performance[14]. The initial perception was, rightly, that an improvement in efficiency would reduce cost, because a greater efficiency means reduced amounts of the material used, reduced transport costs per watt produced, reduced structural equipment and less cost incurred in acquiring the land area to install the systems [15]. Therefore, the pace of research into achieving an improved efficiency continued through meeting the demands for high quality materials, low resistance contacts and near ideal junctions with an extremely low level of bulk and surface recombination.

a. Surface Recombination

The methods used to prevent recombination include: i) improved surface passivation by optimisation of dopant diffusions through making very high quality Si-SiO_2 interfaces; ii) minimising the area of metal-silicon contacts; iii)making high surface concentration deep-dopant diffusions under metal contacts; and iv) making undoped or lightly doped surfaces except under metal contacts[16].

b. Optical Requirements

The demanding optical requirements are also being met by minimising reflection and ensuring that virtually all the photons with energy higher than the band gap are absorbed. This is being achieved through sophisticated light trapping techniques which maximise the absorption of light by maximising the path length traversed by the photon in the solar cell. The techniques include: i) optimising the backside metalisation for high reflectance, thereby ensuring that weakly absorbed photons will cross the cell twice, or ii) structuring the front cell surface to refract the photons into an angle with a larger path across the cell. Structured front and back surfaces as well as mirrored surfaces which increase the effective path length of the photons by up to 50 times the wafer thickness have also been used[17]. This has resulted in increases of efficiency of about 15% in 100μm solar cells.

c. Ideal Junctions

The need for ideal junctions are being met by reducing junction losses which are due to some electron-hole pairs generated by ultraviolet light very near the cell surface recombining in the heavily doped surface layer before they can contribute to the cell output current. This is done by phosphorous diffusion which, with a sheet resistance greater than 50 ohms/square, can reduce the loss to about 1% of the current, independent of the precise surface concentration and junction depth[18]. It is also being assisted by utilising thin substrates which suffer less bulk minority carrier recombination, and eliminates the need to transport carriers over long distances which leads to voltage losses due to series resistance effects, since the diffusion gradients that drive the cells represent voltage losses.

d. Series Resistance

The series resistance is made of the spreading resistance in the dopant-diffused layers, the bulk substrate resistance, and metal fingers and contact resistance of the metal-silicon interface. This is being reduced by using closely spaced finer fingers to reduce the shading effect as well as increasing the contact coverage fraction, the surface doping concentration to reduce the specific contact resistance and by choosing inherently low resistance metals.

2.1.4 Theoretical Peak Efficiencies

These improvements have seen the saturation current density of silicon solar cells (a measurement of recombination losses) being reduced by a factor of about 10,000 and the efficiency rise from the 6% achieved in 1954 to the present day efficiency which is excess of 20% [19] in monocrystalline silicon solar cells. This is close to the thermodynamic limit which is about 30% [20] The theoretical peak predicted efficiencies for any material are 37.9%, 37.3% and 33.0% respectively[21] for the most widely used photon flux densities AM1.5G, AM1.5D[22], and AM0 [23]. AM0 indicates the air mass zero sunlight intensity in space just above the earth's atmosphere at the mean distance of the earth from the sun, AM1 indicates spectra obtained when the sunlight penetrates the surface of the earth through a standard atmosphere at a sun angle of 90° to the earth's surface, AM1.5G indicates a shallower sun angle that increases the atmospheric path length by 50% from the 90° case and simulates the average global spectra with the sun moving across the sky on a standard day, and AM1.5D is the same as AM1.5G except that it simulates only direct spectra from the sun, and is important for concentrating systems since these do not focus diffuse light.

The theoretical peak efficiencies above have not been achieved because of deficits in current, voltage and fill factors of the solar cells. These can be best understood by considering the configuration of the energy band diagram of the standard n/p junction solar cell below.

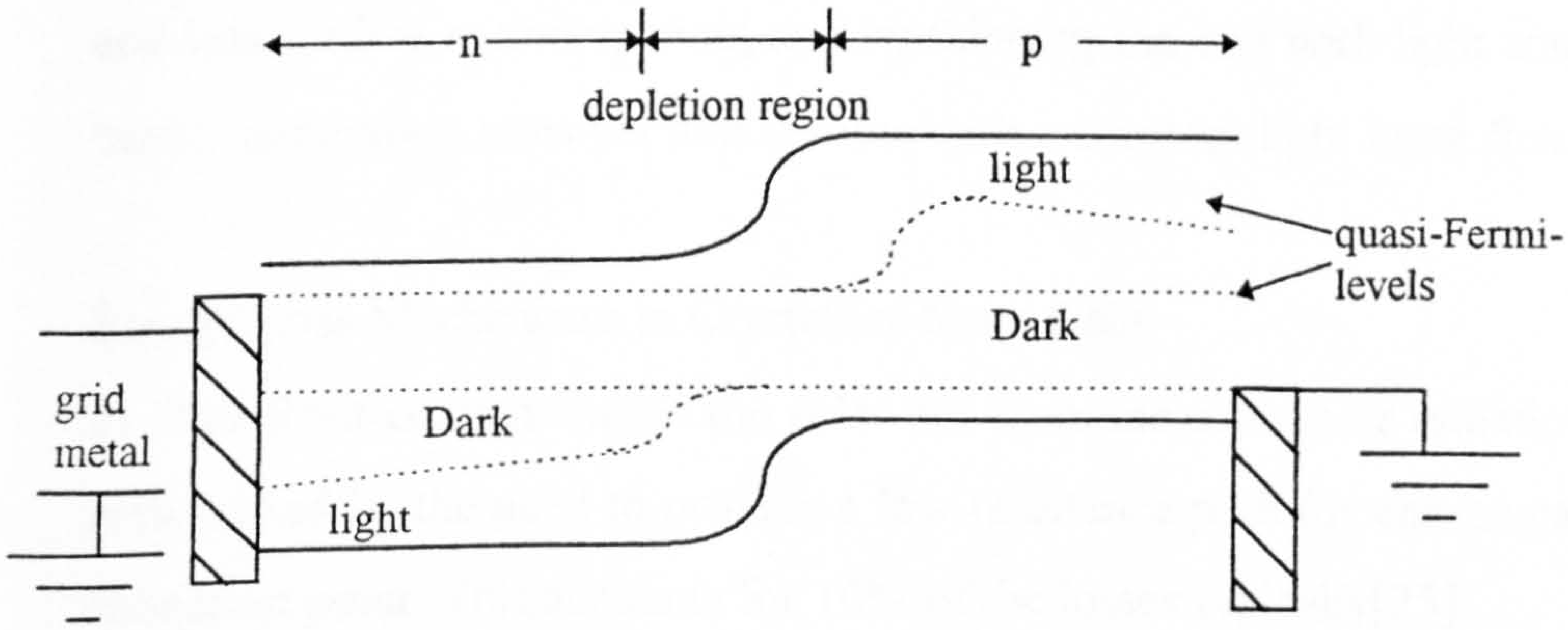

Figure 2.2: Band Energy Structure of p-i-n Solar Cell

The deficit in current is due to the imperfect quantum efficiency and nonzero surface reflection. Voltage deficit is due to low-minority carrier concentrations, and the fill-factor deficit is due to excess leakage currents. Theoretically, any energy of an absorbed photon greater than the splitting of the quasi-Fermi levels is wasted because it cannot be converted into a usable, majority-carrier potential energy difference or voltage that can be transported to an external electrical load. To be absorbed and produce an electron-hole pair, the photon energy must exceed the band gap. The open circuit voltage then increases linearly with the band gap for given majority and minority carrier concentrations. Since the available current decreases with the band gap, there is a maximum efficiency versus band gap that varies with the assumed majority and minority carrier concentrations for a single band gap solar cell. The loss of absorbed photon energy, down to the solar cell output can be divided into three parts i.e.

i) excess photon energy greater than the band gap which is reduced by multiple band gaps that allow photon absorption in sections where the band gap is slightly less than the photon energy[24];

ii) loss in converting light-generated minority carriers into majority ones, which equals the band bending process across the depletion region at the maximum power point and is reduced by splitting the quasi-Fermi levels to as near the band gap (or flat band) as possible;

iii) spacing of the majority-carrier quasi-Fermi levels from their nearest band edge, and this can be reduced to zero with the degenerate majority carrier doping.

The second effect is reduced by concentrating the light to increase the minority-carrier concentration and by decreasing the minority-carrier recombination rates with longer life times and less surface recombination; and by thinning the cell with light trapping for higher minority carrier generation rates per unit volume with a constant light input flux.

Energy Loss Mechanisms in Crystalline Solar Cells

a) The front contact shades the solar cell from incident solar radiation. Reducing its thickness is restricted by the need to provide a low resistance path for charge carriers as they flow to the collection point. This accounts for 10% of the losses typically[25].

b) About 3% of the incident radiation is lost through reflection from the surface of the cell.

c) Some photons pass through the cell and are absorbed in the back contact or generate heat in the cell, because they have energy less than the energy gap.

d) Some photons have energy higher than the gap, so the excess energy is wasted as heat. An optimum band gap of 0.9eV, which takes into account the restriction in c), makes the optimal usage of total incident energy 46% (which is close to the 44% of single crystal silicon cells).

e) Collection losses due to charge carriers not reaching the contacts and thus, recombining and generating heat have been reduced to less than 5%. The reduction is restricted because while the recombination rate can be reduced and the movement of charge carriers across the barrier improved, the spatial distribution of the carriers when they are generated cannot be changed because it depends on the absorption characteristics of the silicon and the spectral distribution of the radiation.

2.1.5 Effects of Not Achieving Higher Efficiencies

The achievement of efficiencies near the thermodynamic limit without achieving the required cost reduction for competing with conventional generating technologies of power has meant

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concentrations and a second junction would provide 1-3% extra efficiency under a 1.4eV top device band gap. 1.8eV band gap would give 4-6% absolute increase[30]. This is close to the 14% efficiency achieved by triple junction a-Si:H based cells under unconcentrated light. It is also only 2% higher than the best (12%) single junction a-Si:H cell efficiency (1995)[31]. Theoretically, additional junctions add extra efficiency for increasingly better matches between quasi-Fermi level splitting and photon energy when the former concentrations are high. Such predicted multijunction efficiencies are as high as 72% for 36 different band gaps under concentrated sunlight[32]. Multijunctions have great potential for improved performance, especially through increasing their minority-carrier concentrations.

2.1.5.b Concentrator Solar Cells

Concentration of incident light is another development which stemmed from the need to improve the efficiency of solar cells. Operation of solar cells at higher concentration means less area is devoted to high quality wafer material such as silicon, which usually contribute to more than 50% of the manufacturing cost. Apart from making more power available to the cells it also results in higher cell efficiency, since the voltage output of the solar cell increases logarithmically with the concentration[33]. Concentrator cells have 4-5% advantage in absolute efficiency over non-concentrator cells, but usually only 85% of the power of sunlight is the direct beam, which is available for concentration. The concentrator cell temperature is also 5°C higher and the Fresnel lens in the module is 85% transmissive to sunlight [34]. Therefore, the power output from the state-of-the-art flat-plate and the concentrator silicon module efficiencies may be similar.

Concentration is usually achieved by the use of Fresnel lenses, classic lenses or reflective optics[35]. Concentrators can be line-focusing or point-focusing. A line focusing concentrator is low concentration and focuses incident sunlight into a linear image, using Fresnel lenses preferably with a convex outer surface and configured with prisms in the inner surface . A photovoltaic receiver, consisting of series-connected cells bonded to a waste heat dissipator is placed along the focal line. A structural housing supports the concentrator and receiver, and minimise moisture and dirt infiltration.

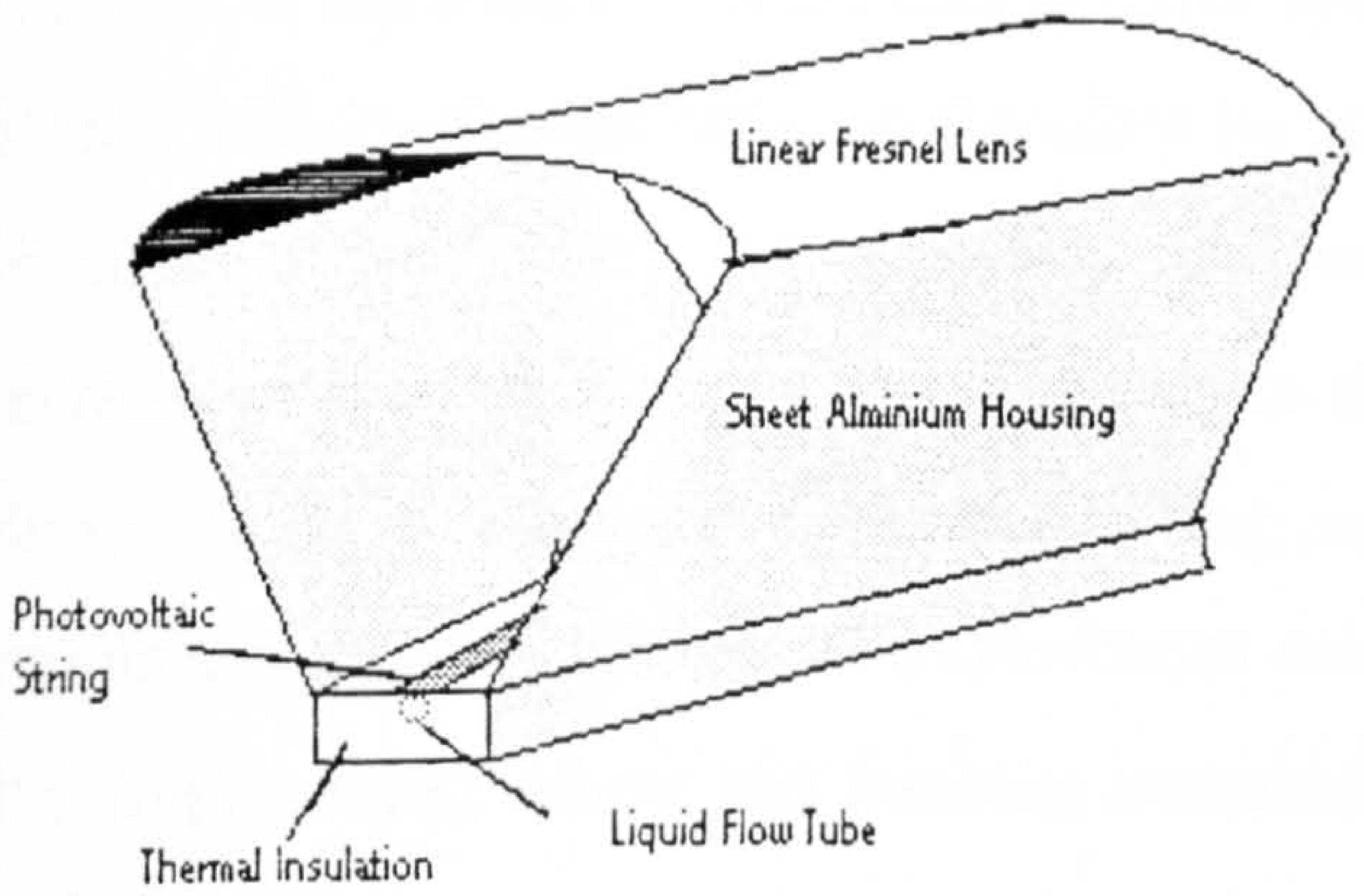

Figure 3a: Line Focusing Concentrator

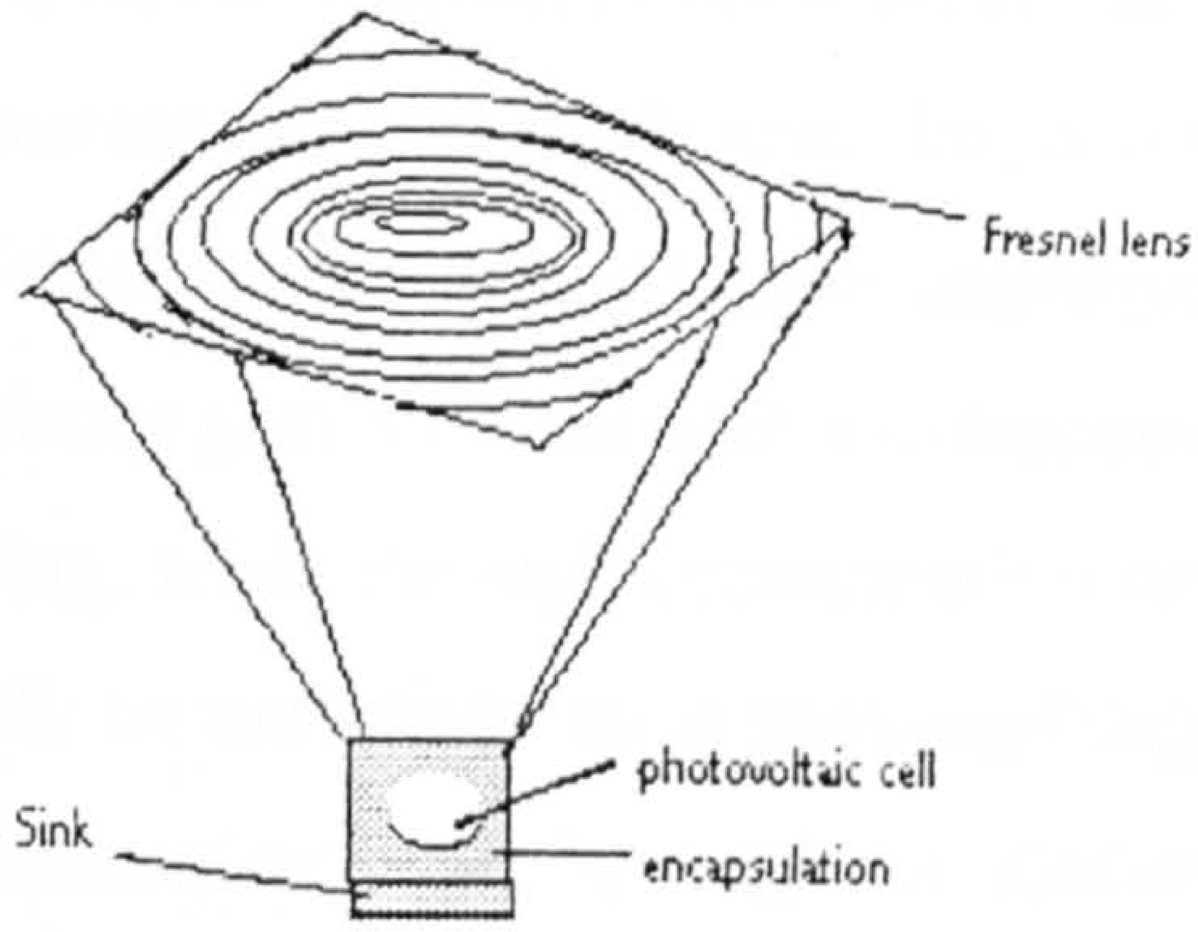

Figure 3b Point focusing Concentrator

A point focusing concentrator has higher efficiency and focuses the light at a point which can be a solar cell. High concentration systems need a tracking mechanism to keep the cells in focus. This mechanism can be governed by a sensor which monitors the position of the sun., or may be controlled by a learning system which computes the required position of the concentrator. Linear optics only require single-axis tracking, while for point focusing double-axis tracking is necessary. Low concentration systems are stationary, and they can collect substantial amounts of diffuse radiation, especially if they are based on devices casting rays on the solar cell from a wide variety of directions. This is attractive to tropical countries with a high amount of solar energy, which is partly diffuse.

There are two groups of silicon concentrator solar cells. One group is similar to flat-plate cells, and is fabricated on doped material usually p-type, and operate in a regime where the density of the photogenerated electron-hole pairs in the silicon never approaches the dopant density. These cells are said to operate under low level injection conditions. The second group uses nominally undoped substrates, with the photogenerated carriers not only necessary to generate voltage but also to lower the internal resistance drops within the cell.

The use of concentration can directly reduce the effects of the cost of the solar cell on the final cost of the power generated by the system. If the cost of concentrating the light is significantly less expensive per unit area than the cost of flat plate modules, then concentration allows a lower price. Since the cost of the concentrator itself dominates at higher concentration ratios, the cost of the solar cell in the concentrator system is a smaller fraction of the total system cost. Higher efficiency solar cells can therefore be used to increase system efficiencies. Improvements in solar cell efficiency are important until such a time as the cost of such improvements increases the entire system proportionately to the efficiency gain. Concentrator systems have the disadvantage of requiring dynamic focusing and cooling, while the high concentration systems requires a tracking system. The drawbacks can actually be capitalised on in building-integrated PV applications, where the tracking concentration system can also be used for shading the building.

2.1.5.c Thin Film Solar Cells

Research into thin film materials was brought about by the need to reduce the manufacturing cost through using less semiconductor material. Thin-film solar cells include hydrogenated amorphous silicon (a-Si:H), polycrystalline silicon (poly-Si), and compound semiconductors such as cadmium telluride(CdTe) and Copper Indium Diselenide($CuInSe_2$ or CIS).

2.1.5.ci. Amorphous silicon cells

These consist of a thin-film, 1μm thick, much less than that of typical crystalline silicon cells which is 100 - 200μm, because amorphous silicon has higher optical absorption coefficients in the maximum solar energy wavelength region of 500A. This is due to the absence of long range periodic ordering of its constituent atoms which results in a lack of defined crystal momentum conservation for optical processes and therefore large absorption coefficients. These cells, therefore have a high material yield. Amorphous silicon also has a lower growth temperature (200°C - 400°C) and this should give a reduced payback period.

However, the high density of defects in the energy gap makes it impossible to effectively dope the amorphous silicon as this requires a large charge to change the position of the Fermi level which cannot be compensated. It is therefore difficult to change the conductivity type of doping of a-Si. It also exhibits poor transport properties due to the high concentration of defects caused by the relaxation of the constraint of a periodic lattice with rigidly assigned atomic positions[36]. This arrangement gives strained, weak and non-existent bonds which results in defects which impede the progress of carriers and promote carrier trapping and recombination. It was found that hydrogen complexes with these defects and saturates the dangling bonds, thereby making it possible for a-Si to be doped either p-type using boron or n-type using phosphorous. This resulted in hydrogenated amorphous silicon(a-Si:H) [37]. However, high contents of hydrogen increases the optical gap and decreases the corresponding absorption coefficient. Therefore, the hydrogen may also complex the desirable unsatisfied bonds due to substitutional doping. The hydrogen bond also weakens with increasing illumination This means that the cell experiences a light-induced efficiency degradation whereby prolonged exposure to light induces metastable changes in the intrinsic layer of a-Si in the cells, because the hydrogen incorporated over a range of bonds results in bonds with a distribution of strengths, and these relatively weak bonds can be broken by locally released energy from electron-hole pairs recombining at higher energy. This creates additional defects ,increasing the density of trapping and scattering states(the Stoebler-Wronski effect) [38]. The cell therefore acquires an equilibrium at a lower efficiency than at manufacture. The process can also be caused by carrier recombination when electrical stress is applied through forward biasing the p/i/n diode.

The hydrogenation of a-Si is therefore essential to achieving high quality cells and the minimal requirements of the deposition process include low contamination levels from impurities such as Na, O_2 ,C and N; critical film thickness control and excellent uniformity for the large area cells. Thus, there are many methods for preparing a-Si:H such as the plasma-enhanced chemical vapour deposition (PECVD) or glow discharge (GD) deposition, photo-CVD, sputtering and hot wire assisted chemical vapour deposition method. PECVD and GD meet all the minimal demands[39, 40]. Photo-CVD has problems in forming uniform films, while sputtering requires a high hydrogen content and results in wider band gap material than the GD process.

Amorphous silicon cells have since evolved from the low efficiency p/i/n devices prepared by the glow discharge decomposition of silane[41], through the simpler Schottky diode devices which reached an efficiency of 6%[42]. The latter were superseded by p/i/n homojunction devices[43] whose efficiency was exceeded by heterojunction p/i/n devices whose efficiency reached about 8% by utilising an amorphous silicon carbide (a-SiC:H) p-layer to form the light incident front junction[44]. 10% efficiency was achieved by preparing heterojunction devices on textured substrates to yield a markedly higher current[45], while efficiencies of about 12% were achieved through grading of the optical band gap of the p/i interface to reduce interface recombination which led to a substantial increase in open circuit voltage, short wavelength response, and fill factor [46]. Cell efficiencies as high as 13.7%, which stabilise to 10%, have been achieved through use of multijunction, multi-band gap devices which give stabilised performance[47].

The photodegradation, which can lead to efficiency decreases of between 10% and 25%has led a-Si:H to be confined to the low power device applications while its introduction to high power applications has been limited. The degradation is self-limiting and this may be due to the recombination of the excess carriers with the photoinduced carriers successfully competing with the degradation process or due to the limit in the number of defective states available. Efforts have been made to predict the dependence of efficiency on time[48]. Because the Staebler-Wronski effect is dependent on the thickness of the intrinsic layer, it has been found possible to stabilise the degradation by splitting the layer into separate layers to form multijunction cells. Stabilising the degradation under 15% after the initial degradation has been achieved[49]. Stabilised module efficiencies of about 8.75% using double junction a-Si:H/a-SiGe:H cells [Solarex][50], and of 10.2% using triple junction a-Si:H/a-SiGe:H/a-SiGe:H cells [United Solar Systems Corp.] have been achieved.

The photodegradation being sensitive to light intensity and duration of exposure made a-Si cells excellent material for small devices operated by low intensity light such as calculators, but it decreased the chances of a-Si modules being used for large scale power production. However the ability to stabilise the degradation using multijunction cells and the ability to document the equilibrium efficiency has made it possible to expect that module production would increase from the present 62MW/year which is 21% of the global production[51]

2.1.5.cii. Thin Film Polycrystalline Silicon Cells

Polycrystalline silicon can also be used as narrow band gap material similar to the a-SiGe:H used in stacked a-Si:H solar cells or for low cost poly-Si thin film solar cells[52]. The silicon has weak light absorbing properties. Therefore, to achieve significant light absorption in the thin cells light trapping techniques such as texturing can be used to achieve optical lengths of up to 20 times cell thickness. Cell thicknesses of less than 10μm are a possibility. Diffusion lengths of 50 to 80μm means lower quality material can be used and higher doping levels tolerated. This gives higher cell voltages. Short-circuit currents are also high due to high collection efficiencies caused by photogeneration occurring in and near the junction depletion region. The possibility of depositing reduced low quality silicon film layers on low cost substrates makes anticipation of the increased production of high efficiency low cost poly-Si cells reasonable. Efficiencies of 16% have been observed and 12% efficiency on 100mm by 100mm commercial cells have been achieved[53]. 14% efficiency have also been achieved from ultra-thin films using light trapping on textured glass, and new lift-off processes for 4μm layers now exist. 19% efficiency silicon-on-isolator cells have been made.

2.1.5.ciii. Compound Semiconductors: CIS

CIS can either be p- or n-type. It has a direct optical absorption(direct band gap material (0.95eV)) and its absorption coefficient is the highest so far observed[54]. p-n homojunctions have proved to be unstable and inefficient, but heterojunctions with cadmium sulphide(CdS) have produced the best CIS devices. However, the CIS has to be p-type in a heterojunction with CdS because the latter can only be grown as n-type material. Using alloys with $CuGaSe_2$ and $CuInS_2$ to prevent excessive recombination at the interface increases the bandgap of pure CIS and this has allowed increases in the cell efficiencies. CIS has also benefited from the fact that it shares optimum bandgaps for multijunctions and complementary manufacturing technologies with a-Si:H. CIS and a-Si:H are superstrate and substrate device technologies respectively, and they should combine to give a durable glass/glass package. 15.6% efficiencies were achieved in such cells, [57] giving large area (0.4m^2) tandem modules with an efficiency of 10.1%[58]. However, the material with the highest efficiency(15%) which could be used for the top cell, CdTe, has a band gap which limits the current into the bottom cell. Therefore an efficiency of only 9.9% has been achieved in a CdTe/CIS mechanically stacked cell. A combination of high efficiency thin film GaAs based cells and CIS has however given an efficiency as high as 23.1%, though this is for space applications.

Large scale production of CIS modules is not yet in existence, but the projected costs of Cu(In, Ga)(Se, $S)_2$ modules have been estimated to range from 0.6 ECU/W_p to 1ECU/W_p

2.1.5c.iv. Compound Semiconductors: Cadmium Telluride

CdTe has a band gap of 1.44eV, and like CIS can absorb about 90% of the incident photons in a 1μm thickness. Therefore, thicknesses of 1 to 3μm are sufficient for PV applications.. Historically, the development of CdTe devices have been prevented by material technology which meant that deep traps existed in the cells and these reduced carrier lifetime in the material. It was also difficult to make low resistance contacts to p-type CdTe which did not degrade with time. The problem with deep traps has been reduced but that of low resistance contacts has proved to be more difficult. However, improved material technology resulted in single junction CdTe cells with projected maximum theoretical practical efficiencies of 27.5%, and 18% respectively in the 1980s [61]. The practical efficiency is dependent on material and device technologies and therefore it has since increased. An efficiency of 15.8% has been obtained in a CdTe thin film solar cell with a MgF_2/glass/SnO_2/ CdS/CdTe structure[62]. BP Solar has achieved a small area efficiency of 14.2% in electrodeposited cells, and an efficiency of 10.1% in 706cm^2 modules. The company is setting up a MW production line in California, USA. CdTe like CIS can also be used in multijunction devices with resulting improvements in efficiency.

2.2. Existing Solar Cell and Module Manufacturing Technologies

2.2.1. Monocrystalline Silicon Solar Cells

2.2.1.a Material Preparation

Silicon solar cells are the most widely used solar cells, contributing over 77% of the world module shipments. This is because of its use in the electronics industry and the ease with which that industry's technology can be adopted for solar cells . Crystalline solar cells consist of thin pure silicon wafers (250-400μm thick) made from high purity fine-grained molten polysilicon(metallurgical-grade silicon MG-Si) extracted by using carbon to reduce molten naturally occurring high grade sand or quartz in a furnace. It is further purified to form semiconductor or electronic grade silicon, (SG-Si). The polysilicon still has about 1% oxygen incorporated as an impurity from the melting crucible. In the Czochralski process, boron is added to the polysilicon to make it p-type. It is then seeded to form single crystal silicon ingots, 150mm or 200mm in diameter and up to 1.5 m long.. The ingots are then either shaped into blocks and sawn to make square wafers usually 100mm by 100mm, or 140mm by 140mm or ground to uniform diameter cylinders which are sawn into circular wafers with a diameter of 100mm. An inner diameter blade saw or continuous wire cutting using a parallel thin-wire array is used to shape the wafers.

2.2.1.b Cell Processing

The wafers are then etched and textured using either acid or base to remove saw damage and produce square based pyramids which reduce reflection and couple light obliquely to the cells thereby allowing light absorption closer to the surface. Sodium hydroxide is usually used because, though slower, basic etches are more environmentally friendly and give surfaces with smaller reflectivity than acidic etches. Phosphorous is then introduced into the wafer to form a p-n junction (n-on-p) cell by either high temperature diffusion in the vapour or solid state usually using the screen printing technique, or by the quicker, less energy intensive but expensive cold junction ion-implantation technique.

The front and back surfaces have metallised electrical contacts so that the cell can be placed in an electrical circuit. The back contact, made of aluminium usually covers the entire back surface. The top surface contacts are made of layers of silver(top layer) for low resistance and solderability, palladium to chemically isolate the silver and titanium under moist conditions, and titanium for good adherence. Screen printing is the most widely used method of contact formation. It involves painting the entire surface with the metal layer and then etching away the latter using photolithography. This forms a narrow-fingered grid which makes good ohmic contact with the silicon and present a low series resistance while allowing optimum light transmission onto the silicon. However, the most reliable, but prohibitively expensive way of contact formation is vacuum vaporisation in which the metal is melted and evaporated and then deposited on the cell through a nickel mask to form a grid pattern[Figure 1].

The cells are also covered by an antireflection coating which reduces surface reflection. The reflection can be up to 30% in untreated silicon and is reduced to about 10% with a single layer coating or to about 3% with a double layer. Even in low-reflection textured crystalline cells antireflection boosts performance by about 4%.

2.2.1.c Module Manufacture

The cells are used in the form of modules, which consist of a string of series cells connected by soldering copper interconnects on each cell to those at the back of the next cell to give the required voltage. A number of these strings are connected in parallel using heavier gauge bus ribbon to give the required current. The cells are then encapsulated to give reliability over the required lifetime. The modules are therefore made of a stack consisting of a low-iron glass superstrate front layer, a layer of ethylene vinyl acetate (EVA), the interconnected cells , another layer of EVA and a backing layer of tedlar.

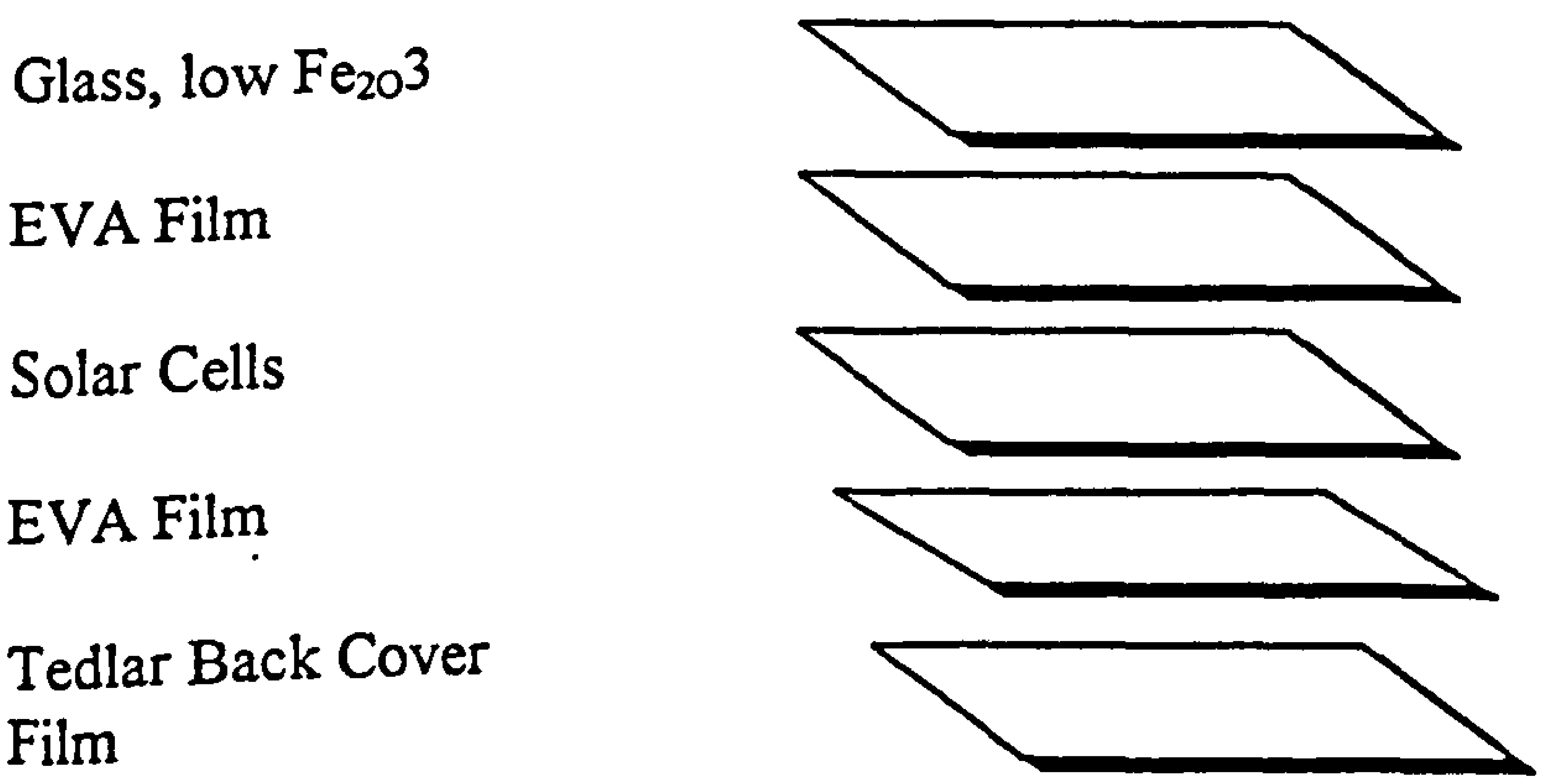

Figure 2.4: Superstrate Module Design [63]

2.2.1.d State Of The Art

The buried contact solar cells(BCSC) shown in Figure 2.5a has allowed the elimination of the limitations of the screen-printed contact process widely used commercially. This has narrowed the gap between commercial and laboratory cell efficiencies, because this cell with efficiencies of 22% and giving module efficiencies of 20% can be manufactured on normal screen printing equipment with additional laser grooving, etching, diffusion and plating equipment[64]. They have been in full production since 1994, with production efficiencies of 17.5% to 18%. A module with an efficiency of 22.3% has been made using passivated emitter, rear locally diffused(PERL) silicon cells with an efficiency of 23% coated with a double layer of antireflection(Figure 2.5b.)[65]

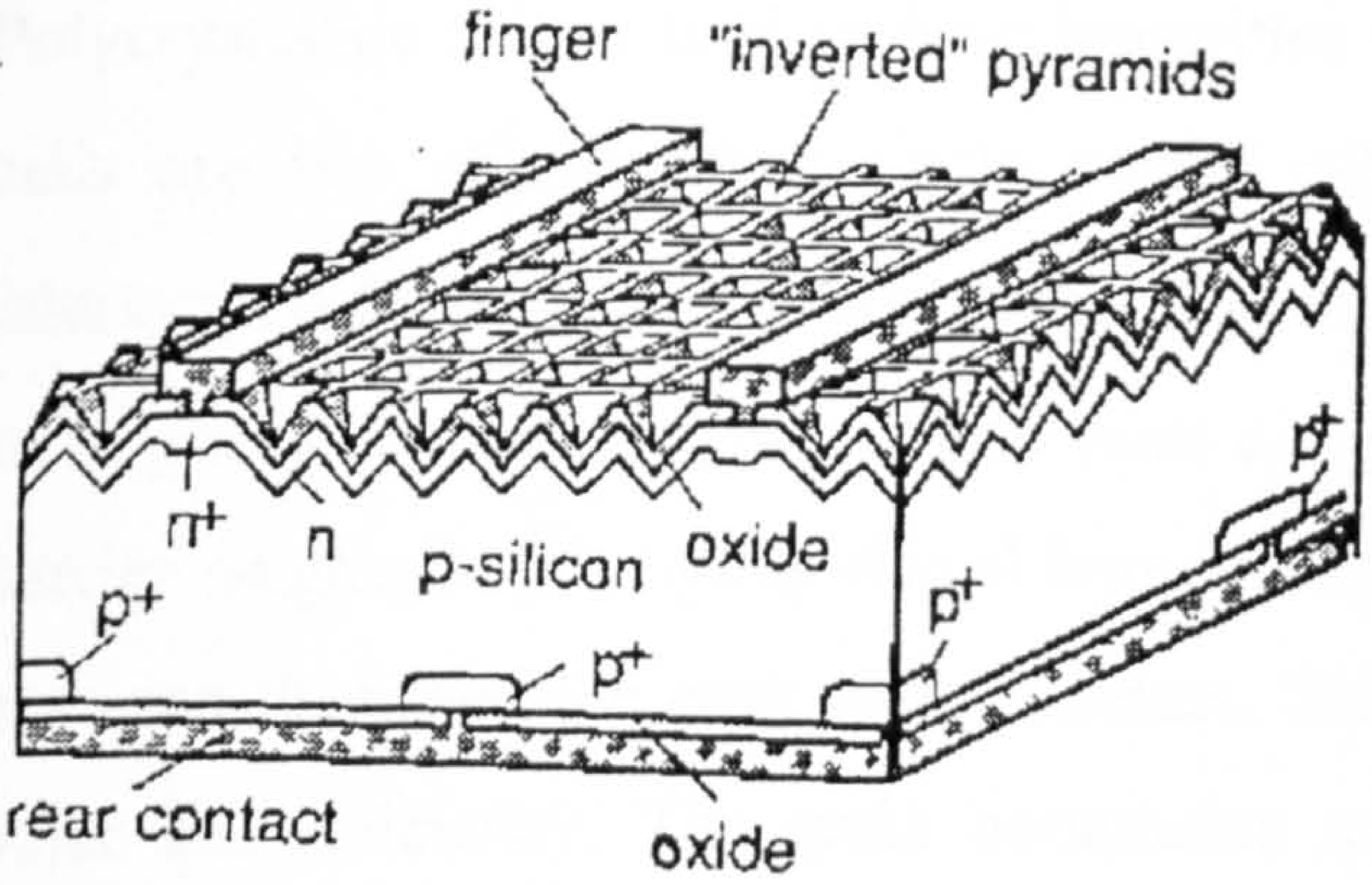

Figure 25b: PERL Cell

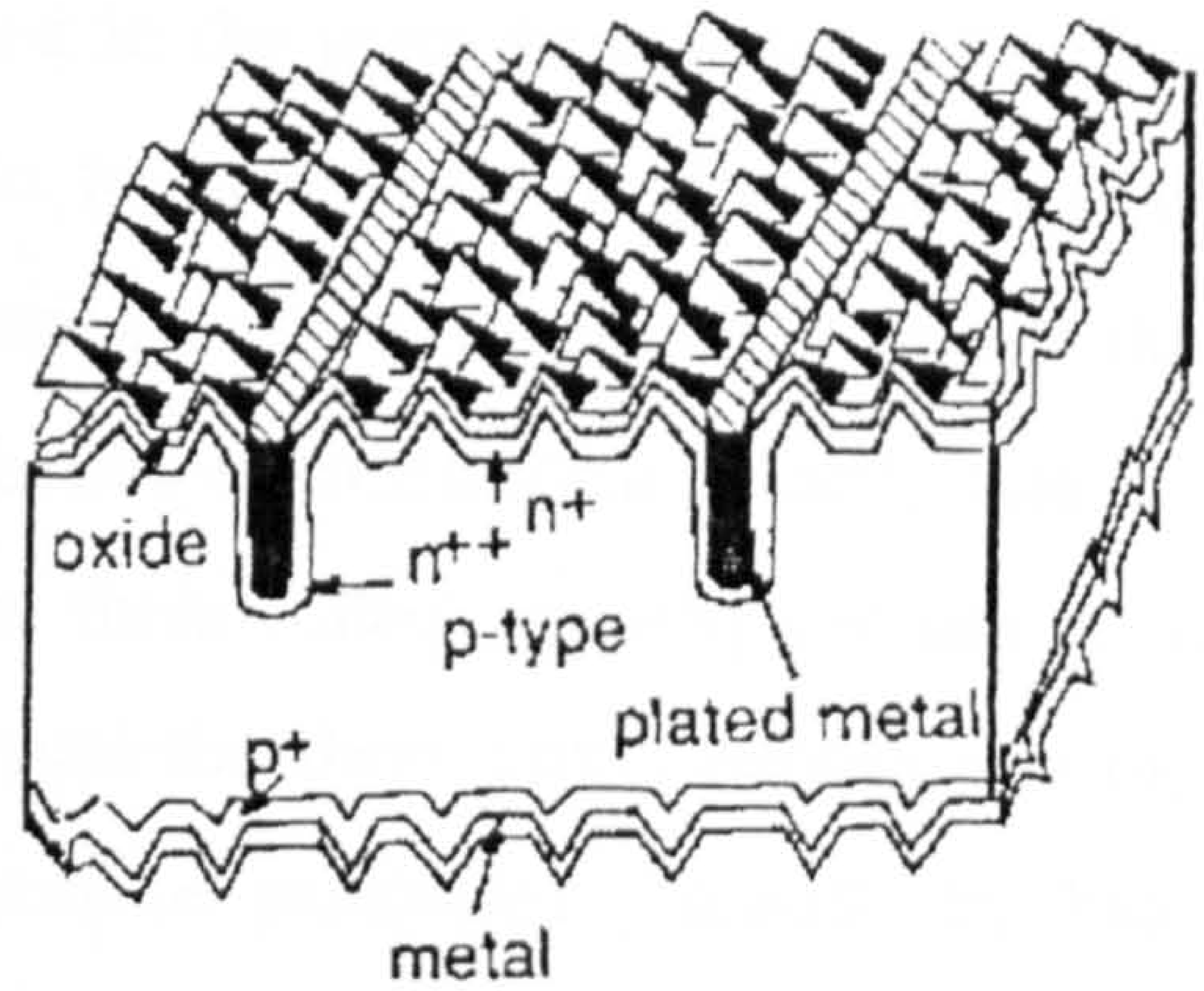

Figure 2.5a Buried Contact Solar Cell

Novel ideas have also been used in the silicon cell technology. These include coloured cells, silicon AC modules, silicon cell PV tiles and shingles. Silicon cells have therefore attained the status of the integrated circuit, which made microelectronics successful by its ability to be adapted to different applications, while its efficiency on a small area of material was continually being improved.

2.2.2. Polycrystalline Silicon Solar Cells

2.2.2.a Material Preparation

These are made from solar grade silicon (SG-Si) which is less pure than that used in the Czochralski process. They however use less silicon than the Czochralski process and may require less pure feedstock than single crystal cells. They therefore are potentially low cost. They are made by allowing molten pure silicon to solidify from a high temperature(1100°C) in a square crucible to give cubic ingots of up to 450mm sides, made of large individual crystallites. The ingots are sliced into 9 rectangular ingots of 150mm by 150mm faces, and then processed just like single crystalline silicon. The conventional preparation is wasteful because the diamond saw used is 0.3mm thick , yet it cuts 0.5mm thick wafers which have to be lapped to 0.3mm to remove sawing damage. Thus, losses of up to 50% in material are possible. A recent multiwire technique, however, cuts stress-free 0.3mm thick wafers with losses of 0.1mm in material, resulting in twice the amount of wafers produced by the conventional method, and raising prospects of lower production costs

Polycrystalline silicon tend to have impurities trapped in the grain boundaries. Therefore, the cells are less efficient than single crystal cells due to limitations of grain boundaries and intergrain defects. The grain boundaries especially those parallel to the junction impede the flow of majority charge carriers and also have a high effective recombination velocity due to large barrier heights in this lightly doped base, which make them collect minority carriers generated between them and the back ohmic contact. This reduces the short circuit current and thus the solar cell efficiency. The grain boundaries are therefore passivated , usually by hydrogen treatment. Surfaces are also passivated with an oxide layer to reduce recombination, and metal contacts are restricted to a small area.

2.2.2.b Cell Processing

The wafers are doped p-type during growth, and introduction of a thin n-type material layer is introduced on one surface by diffusion from a gas or paste in a furnace to form a p-n junction. Antireflection coating or surface texturing using small pyramids is used on the surface of the cells with the same results as in monocrystalline silicon cells . Further reduction in reflection from 5% to 2% have been achieved by decreasing the effective area shaded by the metal finger grids from 5% to 1% while maintaining their optimum series resistance through the use of groves on which the metal fingers have been deposited effectively positioning them on their side with respect to the cell.

2.2.3 Amorphous Silicon Thin-Film Cells

2.2.3a Cell Manufacture

These cells are produced by decomposing a phosphorous doped hydrogenated amorphous silicon alloy and depositing it as a thin film on top of a transparent conductive tin or indium tin oxide layer already deposited on a substrate such as polished steel or glass. The oxide layer is deposited by homogenous chemical vapour deposition, glow discharge, sputtering or spray-on processes. The oxide layer shunts the front side because the poor mobility and small thickness of the silicon result in a high sheet resistance. An undoped layer is then inserted on the doped layer to obtain a low resistivity contact. A third layer of a-Si:H doped with boron forms the collecting barrier and a layer of aluminium deposited on the a-Si:H layer collects the generated current. This gives a p-i-n a-Si cell as shown below.

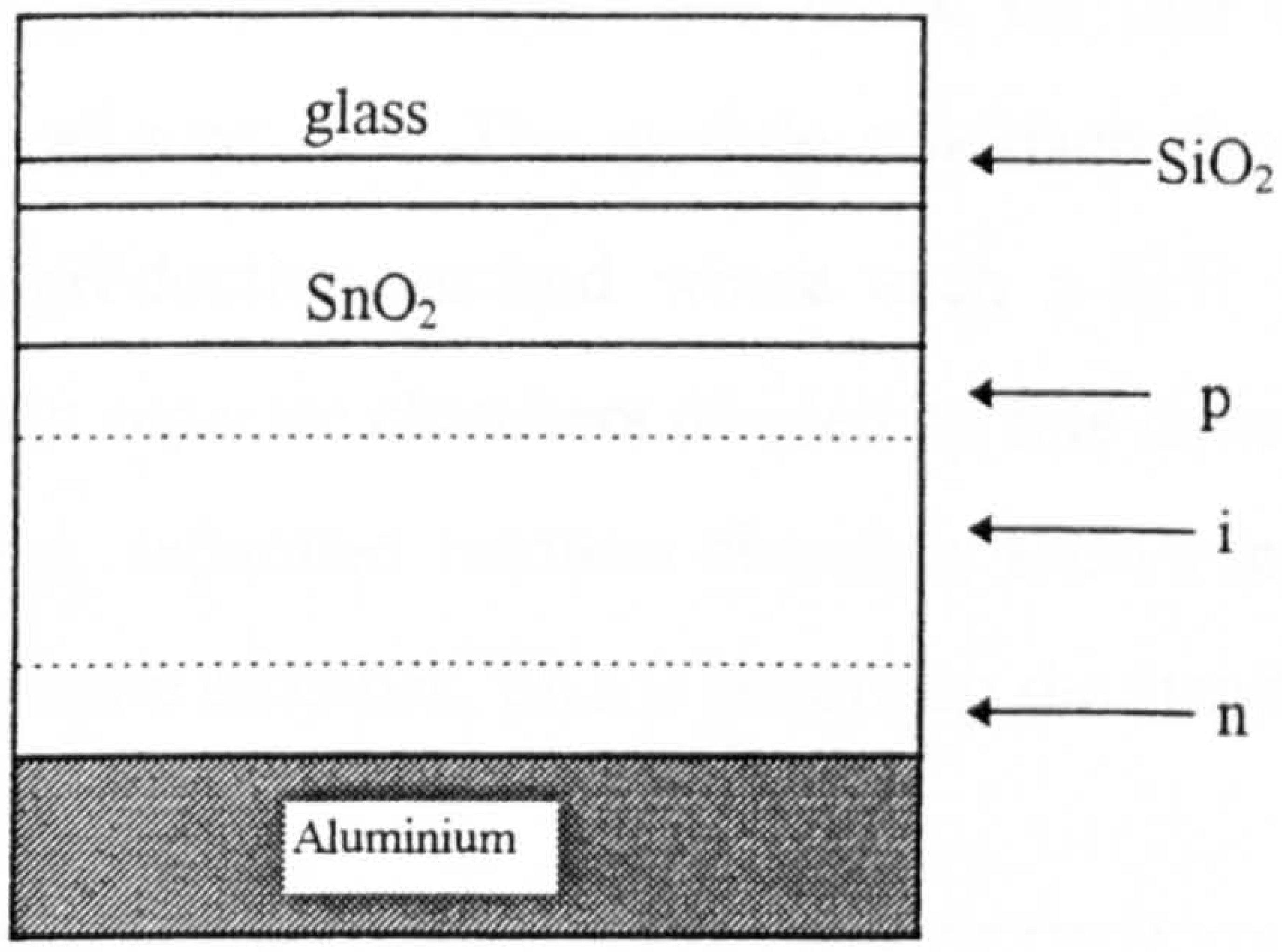

Figure2.6: p-i-n a-Si cell Structure

The boron doped layer has a large absorption coefficient and the minority carriers have an extremely short lifetime. This reduces cell efficiency especially in the short wavelength range. It is therefore, usually replaced by a silicon carbide wide bandgap window layer which forms a heterojunction. This gives a high short circuit current because amorphous silicon carbide is transparent to light. It also gives a high open circuit voltage.

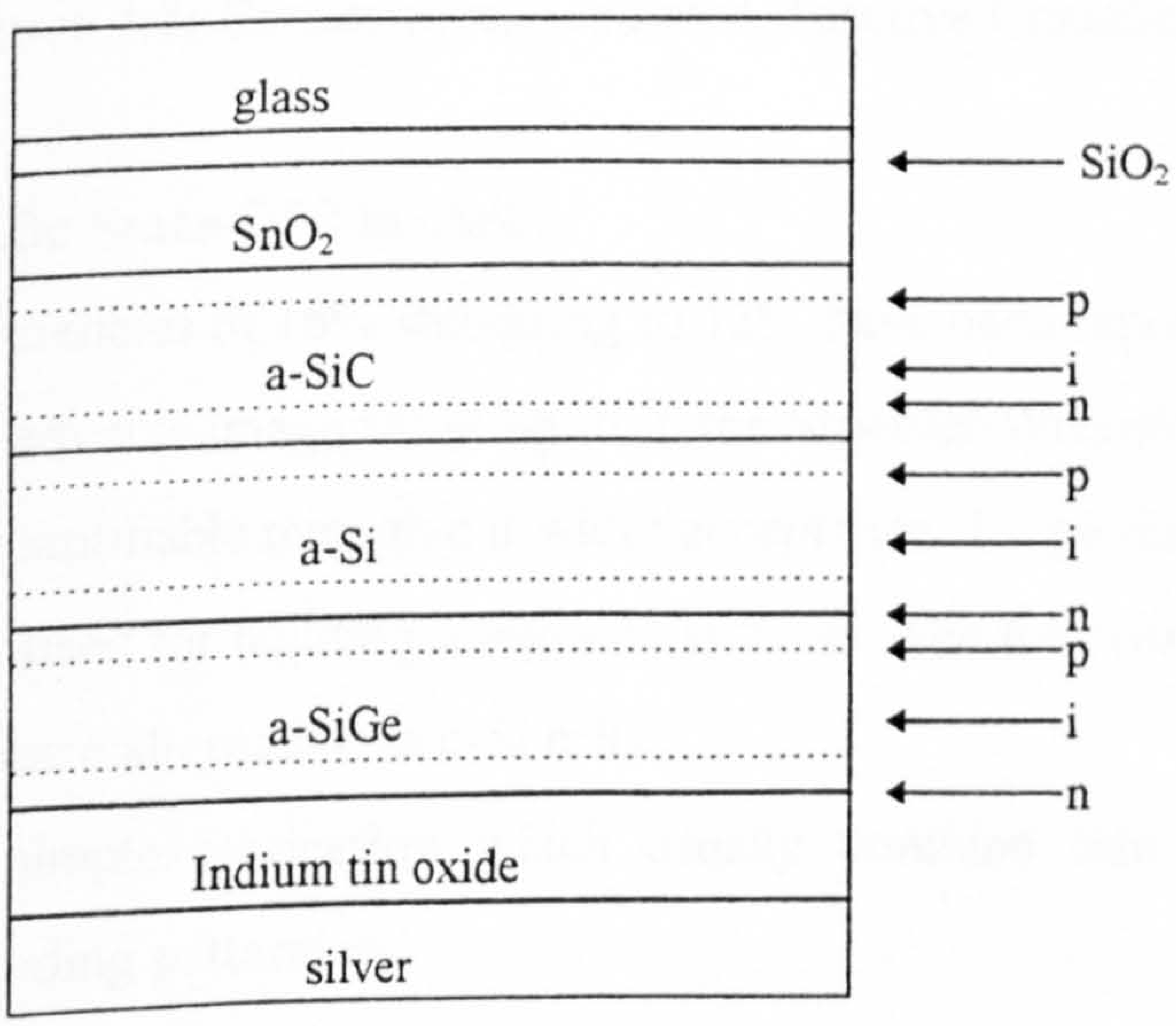

Figure 2.7: a-Si Multijunction Cell Structure

2.2.3b Module Manufacture

Amorphous thin film modules are made by first depositing a series of separated rectangular transparent conducting oxide electrodes on glass substrate. Then the p, i, and n layers are deposited on the electrodes. The amorphous silicon layer is then patterned using a laser scribe. An aluminium electrode is then evaporated through a metal mask. The grooves in the aluminium film are made such that the conductive oxide on one cell is connected to the aluminium electrode of the cell next to it. The module manufacturing methods, include: i) the roll to roll method, a mass production method where each a-Si:H layer is fabricated on a continuous flexible substrate in separate chambers divided by fine divisions; ii) the plasma box method and; iii) the consecutive, separated reaction chamber, shown in Figure 2.8 , in which each layer is deposited in a separate chamber. This is becoming the standard fabrication method.

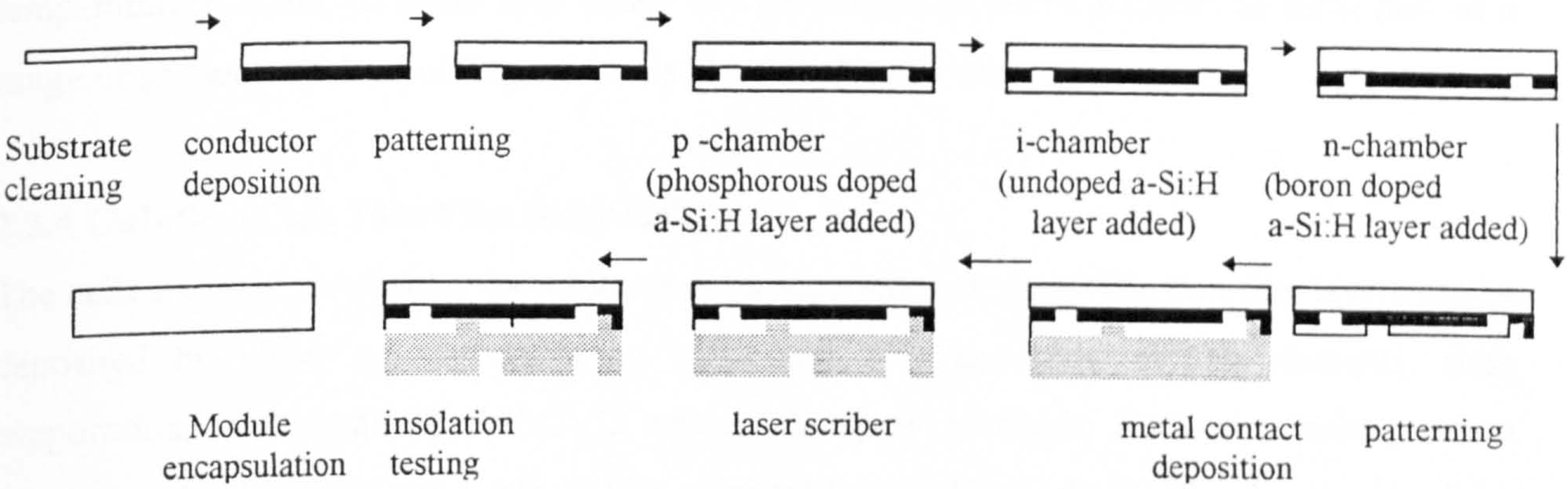

Figure 2.8: Consecutive, Separated Reactive Chamber Method

2.2.3c State-Of-The-Art

Efficiencies of 16% stabilising to 13% have been reported [66].The technology is trying to shed the adverse image resulting from the Stoebler-Wronsky effect, and the fact that the degradation is quantifiable may give it wider acceptance. Large dimension modules have been manufactured and used for building-integrated systems. The following features make a-Si:H cells attractive as a future alternative to c-Si cells:

i. simple fabrication which usually combine thin film and module fabrication processes including patterning;

ii. low temperature fabrication (≤300°C) which allows the deposition of the transparent, conductive oxide thin film on inexpensive substrates such as glass;

iii. gas reactions during fabrication by evaporation which favour processing of large area substrates and therefore enable efficient production of high power modules;

iv. the ability of the cells to be cascade-connected on a single substrate so as to produce high voltages suited for the intended purpose in an integrated submodule structure;

v. the ability to be made into unique modules such as:

- see-through modules : which in addition to generating electricity transmits part of the light as well through small perforated holes in the cell or the use of transparent front and back electrodes;
- ultralight flexible modules made by using transparent plastic film as a substrate in a low temperature process, to make cells which can be bonded to curve surfaces to form part of a range of products such a building materials like shingles and tiles

2.2.4 $CuInSe_2$ (CIS) Thin Film Solar Cells

The cells are configured either as substrate or as superstrate devices. The thin-film layers can be deposited by either of the following processes: co-evaporation of the elements, flash evaporation, laser synthesis, MOCVD, sputtering, spray pyrolysis, electrodeposition, screen printing and sulfurisation and selenisation of metal layers. The highest efficiency devices have been fabricated using co-evaporation from the elements and using sulfurisation and selenisation of metal layers. The metal layers are deposited by either electrodeposition, evaporation and sputtering.

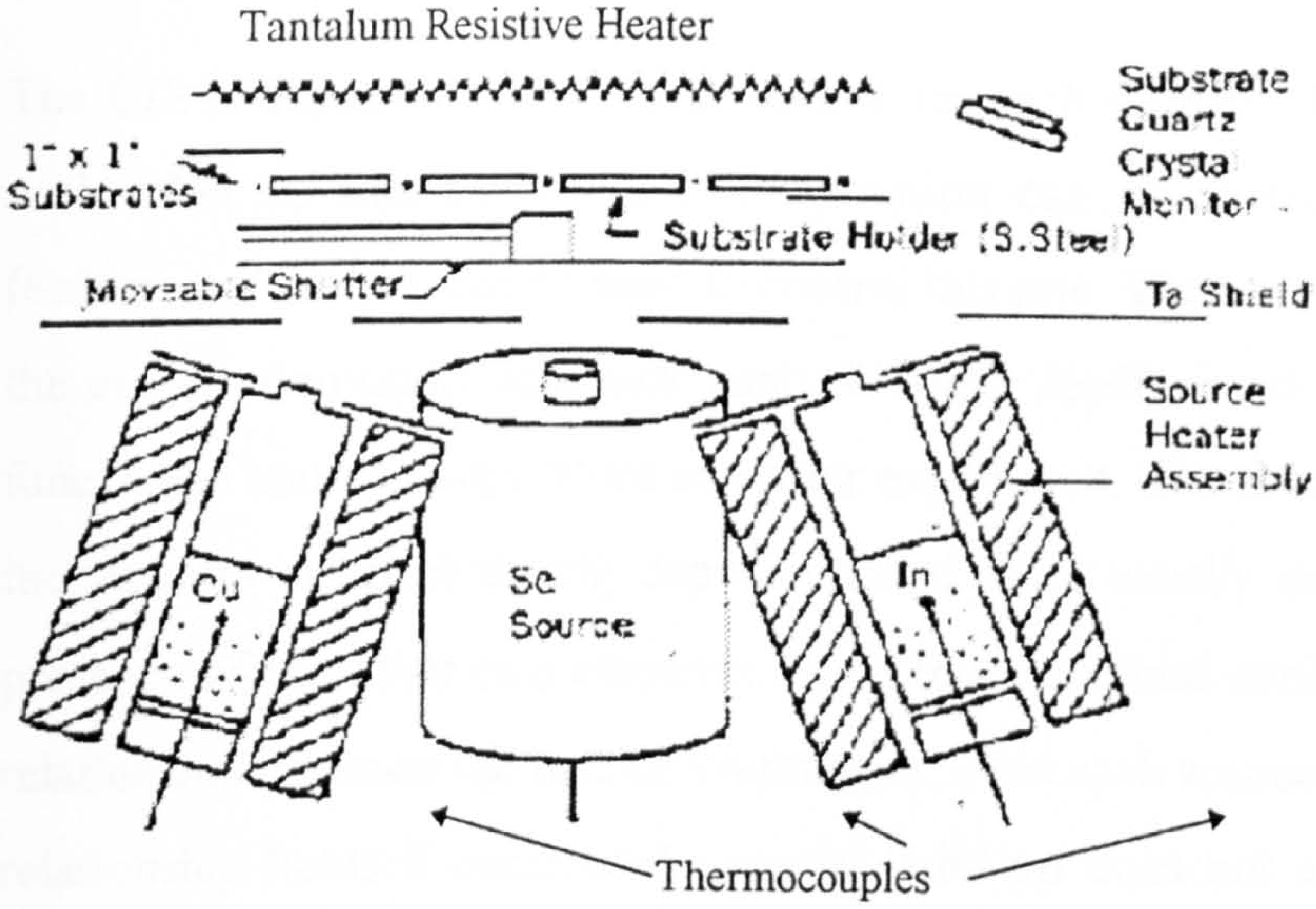

Figure 2.9: Three Source CIS Evaporation [67]

The cells consist of

i. the substrate, of which glass is the predominant substrate, though alumina, metal foils and plastics have been tested

ii. the metal back electrical contact, which can be made of molybdenum, and which can be used as a base for nucleation of the CIS film..

iii. the semiconductor absorber layer, made of either a single thin CIS layer(2μm)or a thick bi-layer(3μm) of high resistivity(copper enriched) and low resistivity(indium enriched) CIS , with the copper induced layer providing the high conductivity required of the layer, and the indium layer providing the low conductivity required to make a stable heterojunction with CdS.

iv. the junction or window layer which optically couples light into the PV absorber layer with minimal reflection and absorption, and transports the photogenerated majority carrier current to the outside circuit with minimal electrical resistance losses. This can be made of cadmium sulphide CdS. The CdS is also usually bi-layer like the CIS for the same reasons.. It is thermally evaporated from a source with sintered CdS powder or pellets and deposited on top of the CIS layer at a substrate temperature of 200°C .

v. the front metal grid or transparent electrode layer, made of tin oxide , indium tin oxide or zinc oxide, which also acts as a partial antireflective layer and

vi. an antireflection layer, which may be magnesium fluoride or antireflective etched glass

The CIS is deposited from 3 sources one for each element. These are heated independently of each other so that their rate of evaporation can be controlled. Either feedback control or feedforward control can be used to control this rate. The source temperature is measured during the evaporation under feedback control. Under feedforward control the rate is measured as a function of source temperature in a prior experiment. The first method requires rate detectors in the vacuum chamber during deposition and these usually suffer from the interference of the presence of the other two elements. The second method avoids this, but it assumes a constant relationship between the rate of evaporation from each source and the source temperature. This relationship holds if condensed material build up does not affect the vapour escape aperture dimensions and if a small proportion of the material in the source is evaporated and topped again before each run. Feedforward control appears to be easier to implement in large-scale commercial production using thermal evaporation

The temperature of the substrate is increased from 350 to 550°C during the CIS deposition. It is maintained at 350°c for the high conductivity layer to be deposited and increased to between 450 to 500°C for the junction forming low conductivity layer to be deposited.

The resulting device structures are as follows:-

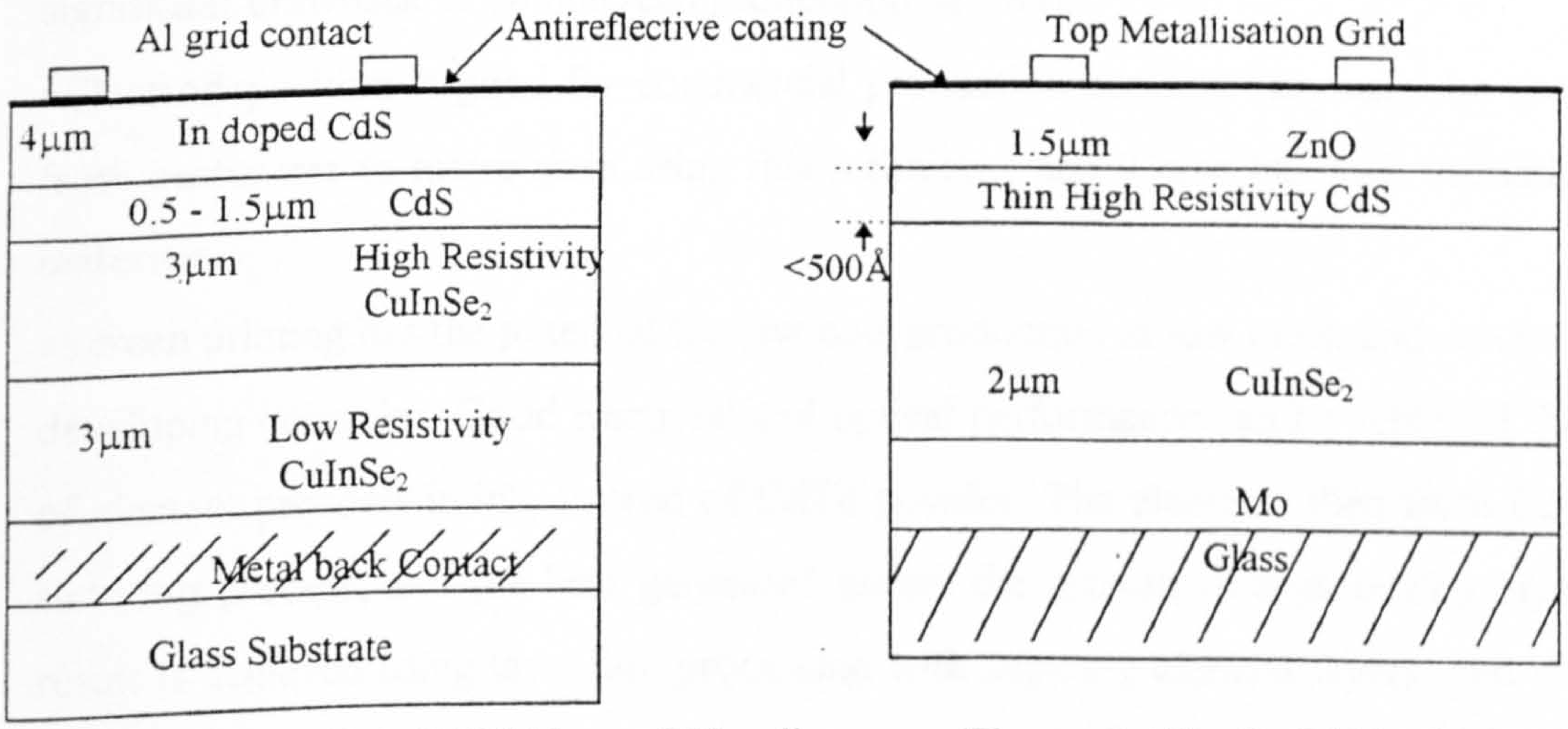

Figure 2.10a: thick CdS/bi layer CIS cell **Figure 2.10b:** ZnO/thin CdS/CIS cell

The cell is finally heat treated in air to 200°C to improve the photocurrent, open-circuit voltage and fill factor. The high temperature annealing period can be up to two days.

2.2.5 CdTe Cells

2.2.5a Material Preparation

Deposition techniques for forming CdTe alloys include atomic layer epitaxy, chemical spray, chemical vapour deposition, close-space sublimation, electrodeposition, sintered films, stacked elemental layer and vacuum evaporation. CdTe can form large grain, oriented films independent of deposition technique, therefore efficiencies in excess of 10% have been achieved by a number of the above techniques. The majority of the CdTe devices are deposited on a glass/transparent conductor substrate in a superstrate configuration. Most of them require some heat treatment after formation and the deposition temperature is significant. Therefore, the glass has to have a high melting point if possible.

• Thermal deposition on to hot substrates at 200-500°C produces n-type thin films with the required low resistance, but p-type films with high resistivity because the active centres are mainly cadmium vacancies and the films tend to have trapping centres close to the centre of the energy gap.

•Closed space sublimation also results in high resistivity films, though the carrier transport is good. The small thickness of the films means the high resistivity does not lead to high series resistances. The real problem is to contact the high resistivity material, and this is a very significant drawback to commercial production of CdTe.

•Electrodeposition is good for commercial production because can easily be used to scale up from centimetre to metre sizes using this technique, and it also has high utilisation of the raw materials.

•Screen printing has the potential for low cost production at low rates, and can be used in developing countries. Good electrical and optical performance can be achieved through the use of element powders in ink, instead of CdTe powder. The elements then form CdTe during the sintering process, and the heat generated assists the growth of high quality layers. The same result is achieved using laser film processing with separate element layers, and it is possible to produce single crystals films of CdTe using this method

2.2.2.b Cell Processing

This involves making CdTe heterojunctions with wide band materials, mainly CdS.

i. The p-type CdTe layer is deposited, usually onto the back contact metal, most likely molybdenum. The strip rolling process used to deposit CdTe onto the molybdenum leads to non-uniformities, even with deeply etched surfaces. The best contact is achieved with sputtered molybdenum deposited on glass or ceramic. However, the sputtering of thick Mo layers, necessary to give reduced series resistance due to the low electrical conductivity of the Mo could limit production. Alternatively, the modules could be made from long thin cells , with an underlying layer of copper for improved conductivity. There are other material that are better contacts than Mo, such as gold alloyed with copper or nickel and copper with indium tin oxide or copper-dope graphite. These contacts result in various cell structures, achieved by different deposition processes as shown in the diagram below as shown in the diagram below.

ii. n-type CdS window layer is then deposited on the CdTe layer to form the heterojunction. The CdS can be replaced by ZnO and ITO which absorb more optically transparent and have lower resistivities

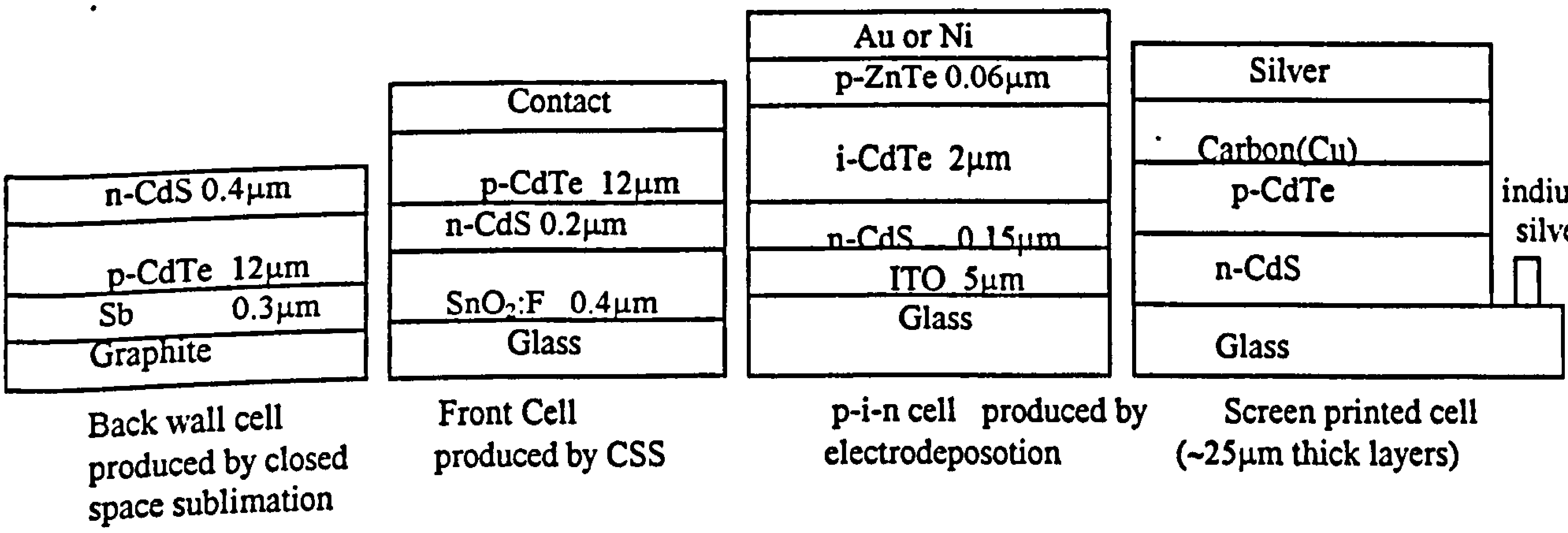

Figure. 2.11 CdTe Cell Processing[68]

2.3 Principles of Operation of Solar Cells

A photovoltaic cell is a diode of large-area forward bias with a photovoltage created from the dissociation of electron-hole pairs by incident photons within the built-in field of the junction diode. It is ideally in the current source class of energy converters. However, in practice it also exhibits some of the properties of the voltage source class of converters[69]. These properties mean its equivalent circuit is as shown in Figure 12 below

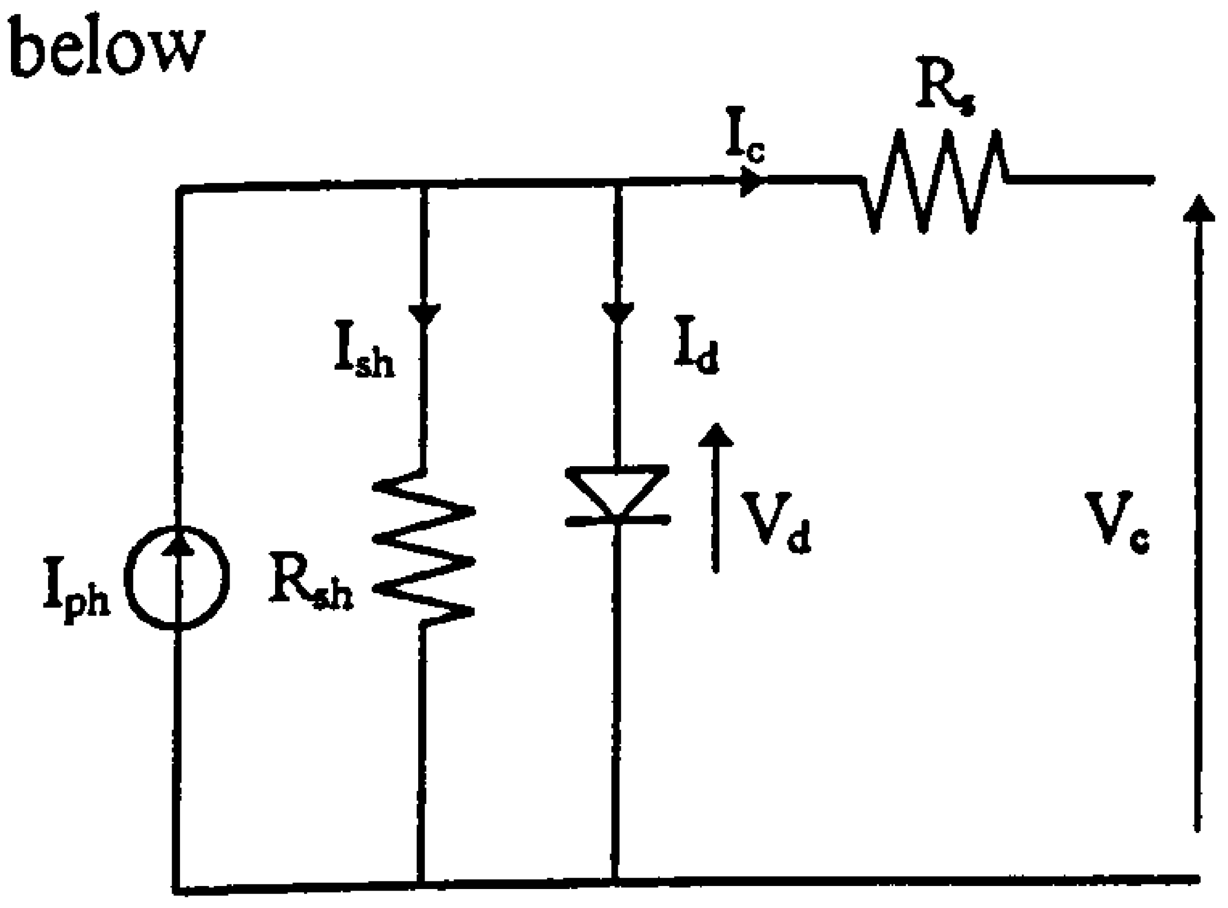

Figure 2.12: Equivalent Circuit of A Solar Cell

One of the biggest development in the evolution of this technology has been the ability to model the performance of the power generator. A number of models can be formulated because of the combined current and voltage source nature of the solar cell.

2.3.1a The DC Model of A Solar Cell

This is based on the single diode equation as given in solid state physics [70], taking into account the curve fitting constant A, the series resistance R_s and the shunt resistance R_{sh} of the cell. It is given by the equation

$$I_c = I_{ph} - I_d - I_{sh}$$

$$= I_{ph} - I_0\left[\exp\left(\frac{q(V_c + R_s I_c)}{AkT_c}\right) - 1\right] - \frac{(V_c + R_s I_c)}{R_{sh}} . \qquad (2.1)$$

where

- I_{ph}, the light generated cell current is given by

$$I_{ph} = I_{sc}E_N + K_t(T_c - T_r) \qquad (2.2)$$

where T_r is the reference temperature and E_N is the normalised irradiance that is irradiance E divided by the irradiance under standard conditions, E_{stc}

• I_{sc}, the short circuit current and V_{oc}, the open circuit voltage are related by.

$$I_{sc} = I_{ph} - I_0\left[\exp\left(\frac{q(R_s I_c)}{AkT_c}\right) - 1\right] - \frac{(R_s I_{sc})}{R_{sh}} \tag{2.3}$$

$$V_{oc} = \frac{AkT_c}{q}\left[\ln\left(\frac{I_{ph} + I_0}{I_0}\right)\right] \tag{2.4}$$

• I_o, the reverse saturation current of an ideal diode is given by

$$I_0 = I_r\left(\frac{T_c}{T_r}\right)^3 \exp\left[\left(\frac{qE_g}{BK}\right)\left(\frac{1}{T_r} - \frac{1}{T_c}\right)\right] \tag{2.5}$$

• I_d, diode current is given by

$$I_d = I_0\left\{\exp\left[\frac{q(V_c + R_s I_c)}{AkT_c}\right] - 1\right\} \tag{2.6}$$

• I_{sh}, the shunt current is given by

$$I_{sh} = \frac{(V_c + R_s I_c)}{R_{sh}} \tag{2.7}$$

• E_g, the band gap energy is given by

$$E_g(T) = E_g(0) - \frac{aT^2}{T + b} \tag{2.8}$$

with a and b found by experiment to be 0.0007eVK^{-1} and 1100K in silicon cells [69];

• T_c, the cell temperature is given by

$$T_c = T_a + \frac{E}{800}(NOCT - 20) \tag{2.9}$$

The derived equations cam be best illustrated by the two graphs in Figure 13

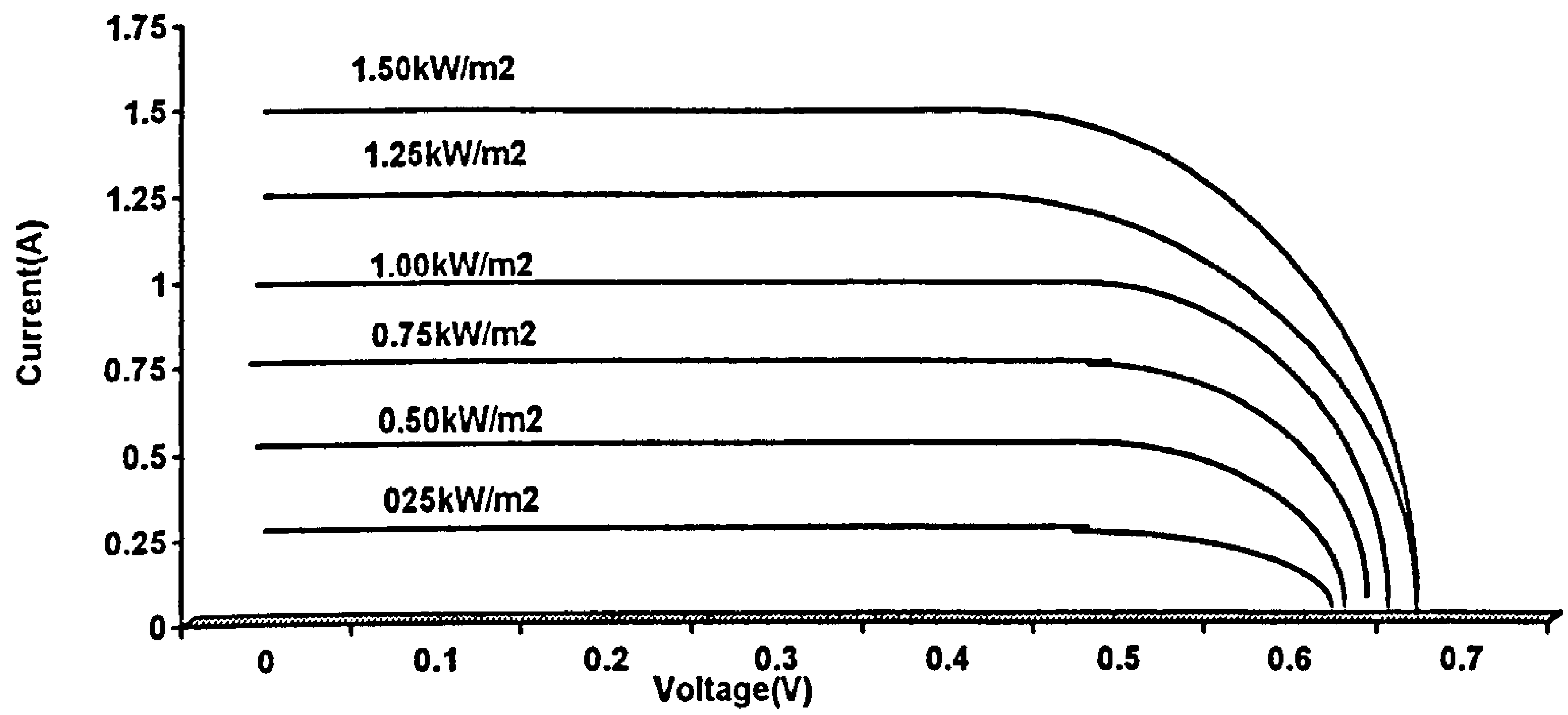

Figure 2.13a: Influence of irradiance I-V on characteristics at constant temperature

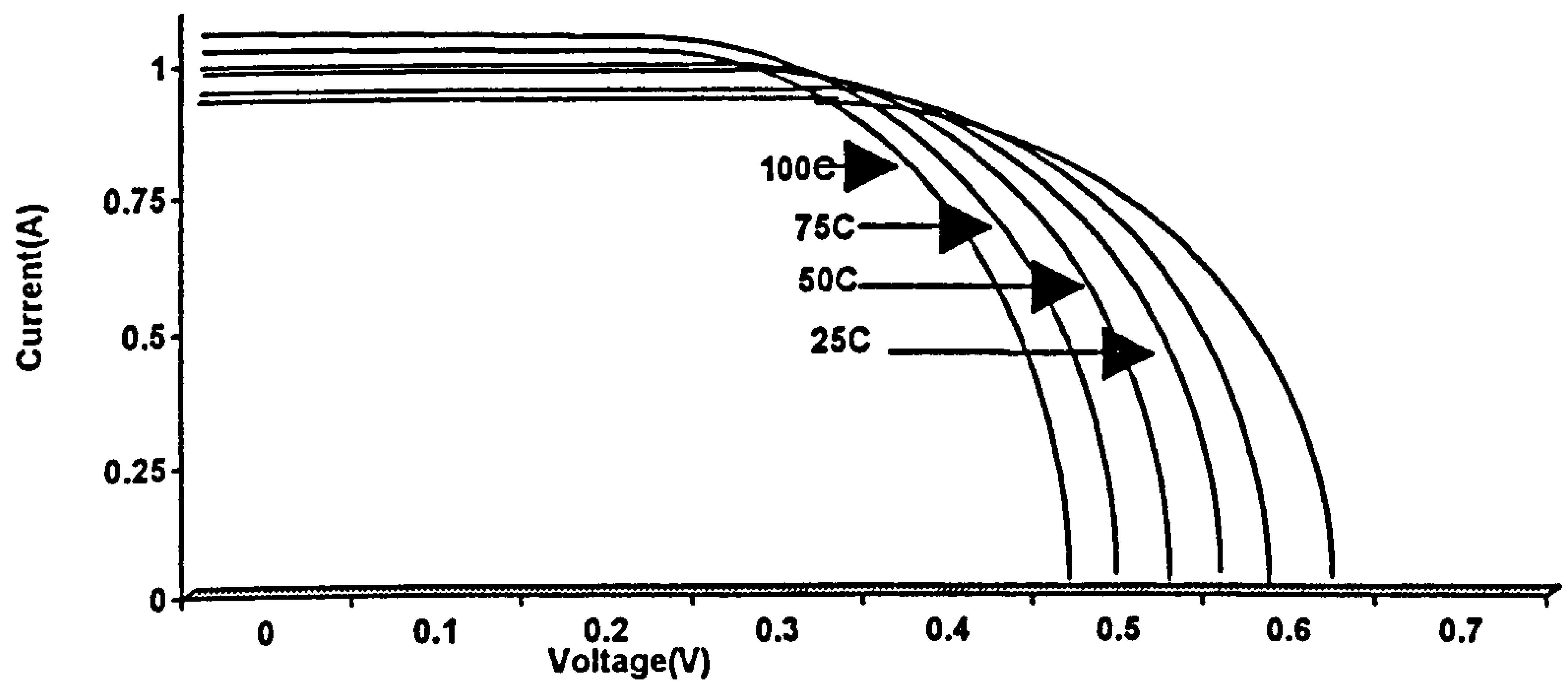

Figure 2.13b: Influence of temperature on I-V characteristics at constant irradiance

These show that the current increases proportionally with solar irradiance, but slightly with increase in cell temperature due to the decrease in band gap energy equation. The voltage increases logarithmically with increasing irradiance level and decreases linearly an increase in junction temperature.

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Measuring I_{sc}, V_{oc} and current I_{cell} at two or more voltages. The difference between I_{sc} and I_{cell} then gives I_d. Corresponding values of V are measured and these together with I_d give a and I_o. Equation 2.17 can then be used to predict the complete I-V characteristics, from which I_{mp} and V_{mp} can be precisely determined from the predicted I-V characteristics. Once the array string I_{sc}, I_{mp}, V_{mp}, and V_{oc} are known, they can be used to predict the solar string power output as function of temperature, irradiation level.

Analytical Model

Solving equation (2.1) for V_c the cell voltage gives[72]

$$V_c = R_{sh}\left(I_L - I - I_0\left\{\exp\left[k_0(V+IR_s)\right]-1\right\}\right) \tag{2.18}$$

this reduces to

$$v = r_p\left(i_L - i - i_0\left\{\exp\left[\alpha(v+ir_s)\right]-1\right\}\right) \tag{2.19}$$

and

$$i = \left(i_L - \frac{v}{r_p} - i_0\left\{\exp\left[\alpha(v+ir_s)\right]-1\right\}\right) \tag{2.20}$$

where , $v = \dfrac{V}{V_{oc}}$, $i_o = \dfrac{I}{I_{sc}}$, $i_L = \dfrac{I_l}{I_{sc}}$

$r_p = \dfrac{R_{sh}I_{sc}}{V_{oc}}$, $r_s = \dfrac{R_sI_{sc}}{V_{oc}}$, $\alpha = k_oV_{oc}$, $.k_o = \dfrac{q}{AkT}$

$i = 0$ when $v = 1$ and vice versa. Therefore

$$1 = r_p\left(i_L + i_0 - i_0\exp[\alpha]\right) \quad \text{and}$$

$$1 = i_L + i_0 - i_0\exp(\alpha r_s)$$

from which i_0 and i_L are determined as

$$i_0 = \frac{r_p - 1}{r_p}\left[\frac{1}{\exp(\alpha) - \exp(\alpha r_s)}\right] \tag{2.21}$$

$$i_L = 1 + i_0\left[\exp(\alpha r_s) - 1\right] \tag{2.22}$$

This allows r_s, r_p and α to be determined from only 3 points on the i-v curve of the cell. The mathematical model of the cell can therefore be completely derived if I_{sc} and V_{oc} are measured.

Other Models

i. Distributed Parameter Solar Cell Model[73]

In most solar cells, the p-n junction, series resistance, and other cell parameters are distributed over a relatively large area, leading to voltage gradients and varying current densities throughout the device. To improve this, first, a second order lumped parameter model is developed. Earlier p-on-n, series as well as other n-on-p cells were found to exhibit 2 distinctly different, dominant p-n junction characteristics which are related to minority carrier diffusion and recombination effects. Many more fully distributed parameter solar cell models were developed using transmission line theory and other approaches primarily intended for solar cell contact and grid-line optimisation work.[74] None of the DPSC models lend themselves in a practical way to solar cell or array performance analysis because essentially all of the solar cell parameters vary with any one or a combination of temperature and illumination intensity, and the parameters I_o, A and R_s are very difficult to measure over all ranges of interest.

ii Empirical Models

An analytical expression of the solar cell I-V curve is not required for computer work. Discrete sets of I-V data points representing the otherwise smooth I-V curve may be stored in the computer memory. These sets of points may be translated point-by-point to the operating conditions different from those for which test data exists.

2.3.1d Selecting the Proper Model

Any solar cell model used for the computerised array analyses must satisfy the following criteria :-

1. It must, accurately, simulate temperature, illumination level, and environmental degradation;
2. It must permit, the manipulation of the I-V curves, as required for predicting the array performance under certain specified array operating conditions. The range of interest and the accuracy are application specific.

2.3.2 Photovoltaic Array Configuration

The power output of a single module is not sufficient for most applications. Therefore they are connected together so that they form an array which can generate sufficient power for a particular application. The operation of the modules in an array is essentially equivalent to that of a string of cells connected in parallel, in that a number of the modules are connected in series to give a string that produces the required current. A number of such strings are then connected in parallel to give the required voltage. Due to the technical inadequacies of manufacturing processes, the non-optimal utilisation of the solar cells and shadowing effects individual modules have mismatched characteristics[75]. These result in electric and thermal imbalances when the modules are connected together. Consequently a module in an array can end up behaving like a power receptor thereby reducing the power output of the array. This problem is alleviated by connecting bypass diodes across the modules so that when they are shadowed or faulty and not generating electricity they do not act as an additional series resistance. The string current is then carried by the bypass diode, which has as low a threshold voltage as possible and which has a sufficient current rating to carry the string current. Each string also has a blocking diode in series with it to protect it from adverse conditions which affect the whole string. The final array arrangement is in Figure 14.

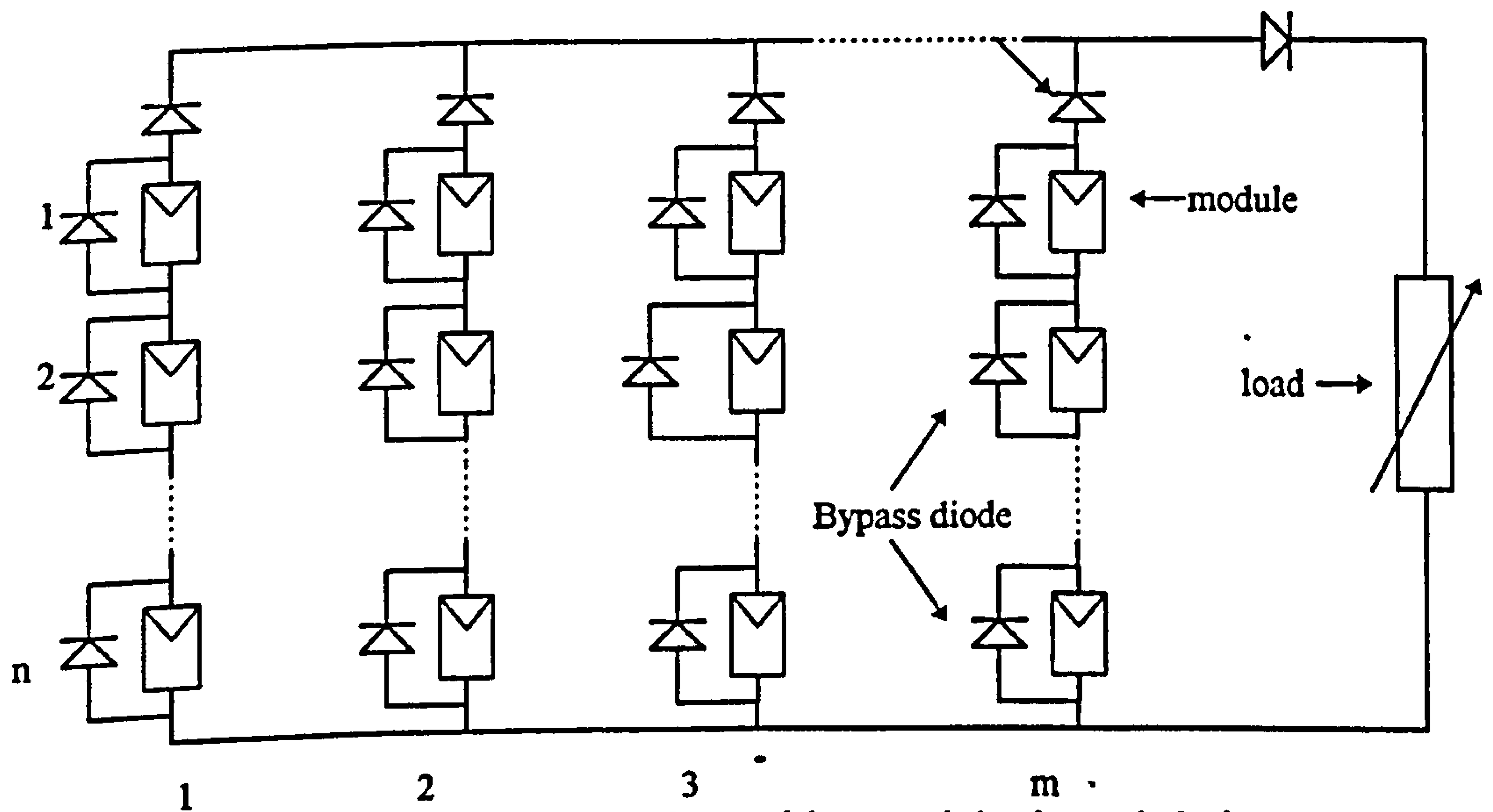

Figure 15: An array of m strings with n modules in each String.

2.3.3 Photovoltaic System Engineering

2.3.3a Load Profile Development

Solar array systems may be designed for a variety of electrical loads. These are rarely resistive and of constant value: converter circuits draw pulsating power of nearly constant magnitude independent of the input voltage. Motors have inductive components. User equipment does not operate at constant power during periods of sunlight, but is switched on and off and may require energy during periods when no sunlight is available. Switching operations may produce transient voltage and current conditions unlike those experienced in circuits that are connected to rotating machine type electric generators.

Rotating machines and batteries are capable of providing nearly constant bus voltage at significantly high, temporary overload conditions. Solar cells, however, have no such capability. A sudden current demand in excess of 10% of the rated maximum power output current at given operating conditions of the cell may cause a temporary collapse of the output voltage of the cell[76]. Therefore it is usually necessary to use a rechargeable energy storage in conjunction with the solar cell array to handle the transient. Considering a load consisting of an electric motor driven pump operating for a short period at long intervals during the day and a constant continuous load. The starting current of the motor determines the maximum power required, hence the ampere rating, the associated wiring and switchgear, though it consumes a negligible amount of energy. The continuous load determines the maximum energy required, though it has the lowest peak current drain. These two factors determine the size of the solar array and the associated storage.

2.3.3b Preliminary Array Sizing

i Module Area Method[77]

Power output capability of an array is given by

$$P_A = E \cdot \cos\Gamma \cdot \eta \cdot F \cdot A_a \qquad (2.24)$$

E = solar radiation intensity W/m^2

Γ = angle of incidence of solar radiation

η = module efficiency

F= sum of all the array design and degradation factors

A_a = effective array area, area covered by modules only

Solving for A_a

$$A_a = \frac{P_A}{E \cdot \cos\Gamma \cdot \eta \cdot F} \quad (2.25)$$

thereby calculating the required array area to meet the load requirements, P_A

ii Cell Area Method

The array area A_a is replaced by the total number of solar cells in the array, N_t, and the area, A_c

$$P_A = E_e \cdot \cos\Gamma \cdot \eta \cdot F \cdot N_t \cdot A_c \quad (2.26)$$

Solving for N_t

$$\Rightarrow N_t = \frac{P_A}{E_e \cdot \cos\Gamma \cdot \eta \cdot F \cdot A_c} \quad (2.27)$$

iii Cell Power Method

The array power, P_A is given in terms of the solar cell power output, P_c and the reference intensity at which the cell power output P_c was determined

$$\Rightarrow P_A = \frac{E_e \cdot \cos\Gamma}{E_o} \cdot F \cdot N_t \cdot P_c \quad (2.28)$$

The required number of cells is N_t

$$\Rightarrow N_t = \frac{P_A . E_o}{E_e \cdot \cos\Gamma \cdot F \cdot P_c} \quad (2.29)$$

2.3.3c Detailed Array Design and Sizing

The maximum power output of a module is [75]

$$P_o = P_O' \cdot E' \cdot F_{RAD} . F_{T_{OP}} \cdot F_M \cdot F_{SH} \cdot F_{BD} \cdot F_{CONF.} \quad (2.30)$$

where

P'_o is the undegraded solar module output at normal incidence at one solar constant, and at reference temperature 25°C.

E' is the effective solar intensity including degradation, and non-normal incidence

F_{RAD} is the solar module degradation factor and is given as the ratio of cell maximum power before installation and after installation of the array

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$$I_{mpav} = \frac{\sum_{i=1}^{n} I_{mpi}}{n} \tag{2.35}$$

I_{mpi}, the current in the ith string is given by

$$I_{mpi} = I_{mp\phi} \cdot (E')_i \cdot \left[1 + \beta'_{Ip}\left(T_{op} - T_r\right)\right] \cdot F_m \cdot (F_{SH})_i \tag{2.36}$$

E' is the effective light level which is incident upon the active surface of the solar cell

β_{Ip}' is the temperature coefficient for maximum power current

2.3.4. DC Power Conditioning

Photovoltaics generated DC power can be used either without being stored first by being supplied directly to equipment such as fans, pumps and thermal systems, or it can be stored first in batteries or fed to the utility grid. Power conditioning units are needed for the optimal operation of the photovoltaic generator and the loads supplied by it as well as for their protection. The power conditioning units that can be used in a PV system include inverters, matching DC/DC converters and charge controllers.

The PV system should ideally be operated as close as possible to the maximum power point(MPP) under all conditions of insolation, temperature and load. This is the point on the current-voltage curve where the product of the current and the voltage is maximum. The benefits of a MPPT can sometimes be minimal depending on the application. For instance, when charging a battery the generator can be operated close to the MPP if the nominal voltage of the battery is chosen appropriately. On the other hand in a grid-connected system the PV system operating voltage is determined by the control algorithm of the inverter. The input voltage of the inverter can be shifted by the MPPT which can be in the form of hardware or software. No extra energy dissipating electronic equipment is therefore required, and, therefore a MPPT is recommended.

A large amount of energy is lost due to mismatch, i.e. the operating points of the loads are far away from the MPP under most insolations[78]. System sizing is therefore done by considering the load line which has the best available match with the I-V curve of the generator. A DC/DC converter is then used to eliminate the mismatch. The input voltage of the converter is kept constant and the output voltage varies depending on the input power and the load characteristics. The converter significantly improves the power available especially at low insolations. This leads to a better starting time for pumps and fans, and therefore converters are usually built in. The most common algorithms for the MPPT involves changing the operating voltage of the PV generator by a small amount at regular intervals, and observing the effect on the output power of the power conditioning unit. If the power increases the operating voltage is changed similarly on the next time step. If it decreases the direction of change is reversed. This makes the operating point swing about the actual MPP.

2.3.5 Inverters

Storage of PV generated power has traditionally been done by batteries. These have to be changed several times during the lifetime of the generator. The battery lifetime has also been observed to be much shorter than anticipated, in the range of 2 - 4 years instead of the expected 5 - 10 years[79]. A charge controller is therefore used as peripheral battery hardware to limit the battery voltage to the manufacturer's specifications of charging and discharging, and to carry out maintenance duties such as charge equalisation, monitoring state of charge of the battery, providing the performance history and acting as energy management systems. These limitations of batteries make them unsuitable for commercial building integrated systems, because the continual change of batteries would increase the cost of the plant . Moreover for medium to high power applications a lot of room would be required for them in these buildings where space is expensive.

Most devices used in commercial buildings are conventionally AC loads because utility power has always been supplied in AC form. The conventional DC motor has also faced maintenance problems due to the presence of commutators and brushes. This has made their reliability to be regarded as low at medium to be high power levels[80]. They also have proved to be more expensive than AC motors, perhaps due to the marketability of the latter. Consequently, in the past it has been considered justifiable to acquire an additional converter stage, the inverter, and use an AC motor instead of buying a DC motor. The final configuration of a PV power supply may therefore end up as shown in Figure 2.16.

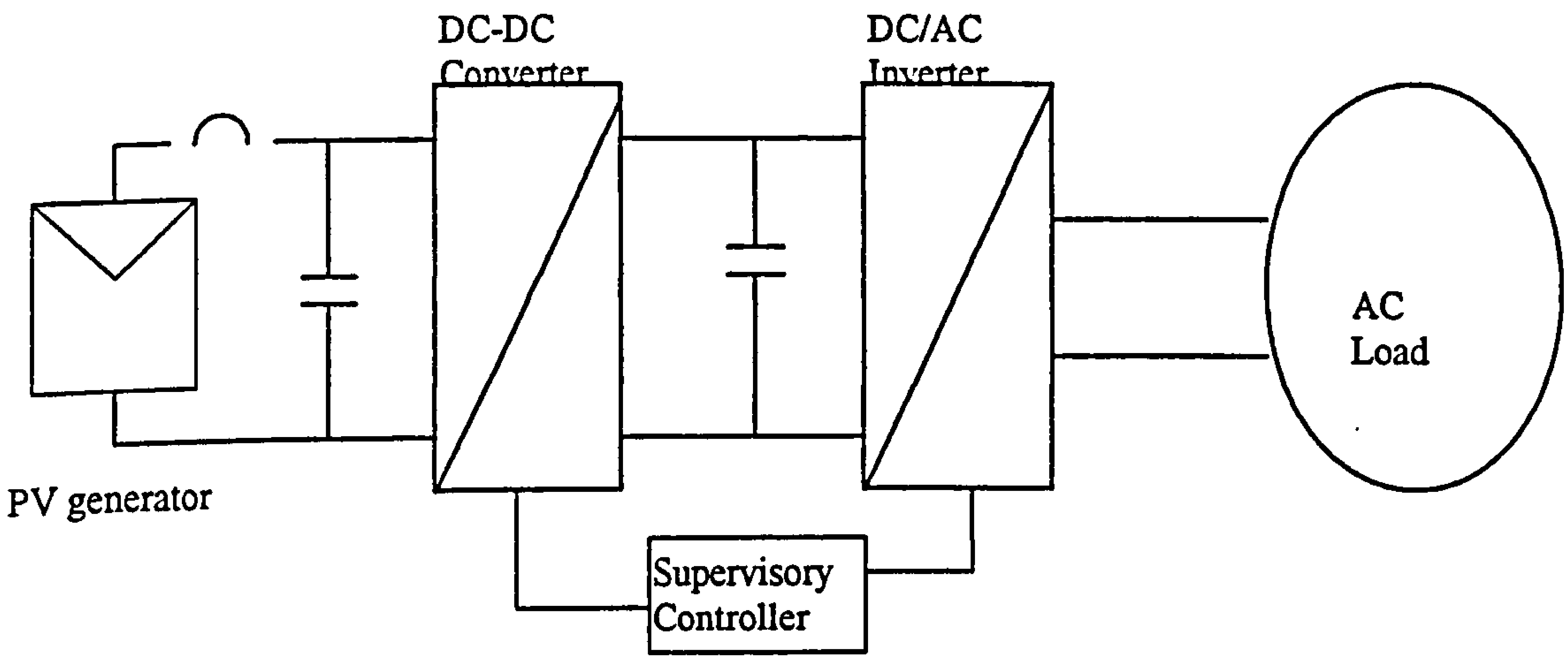
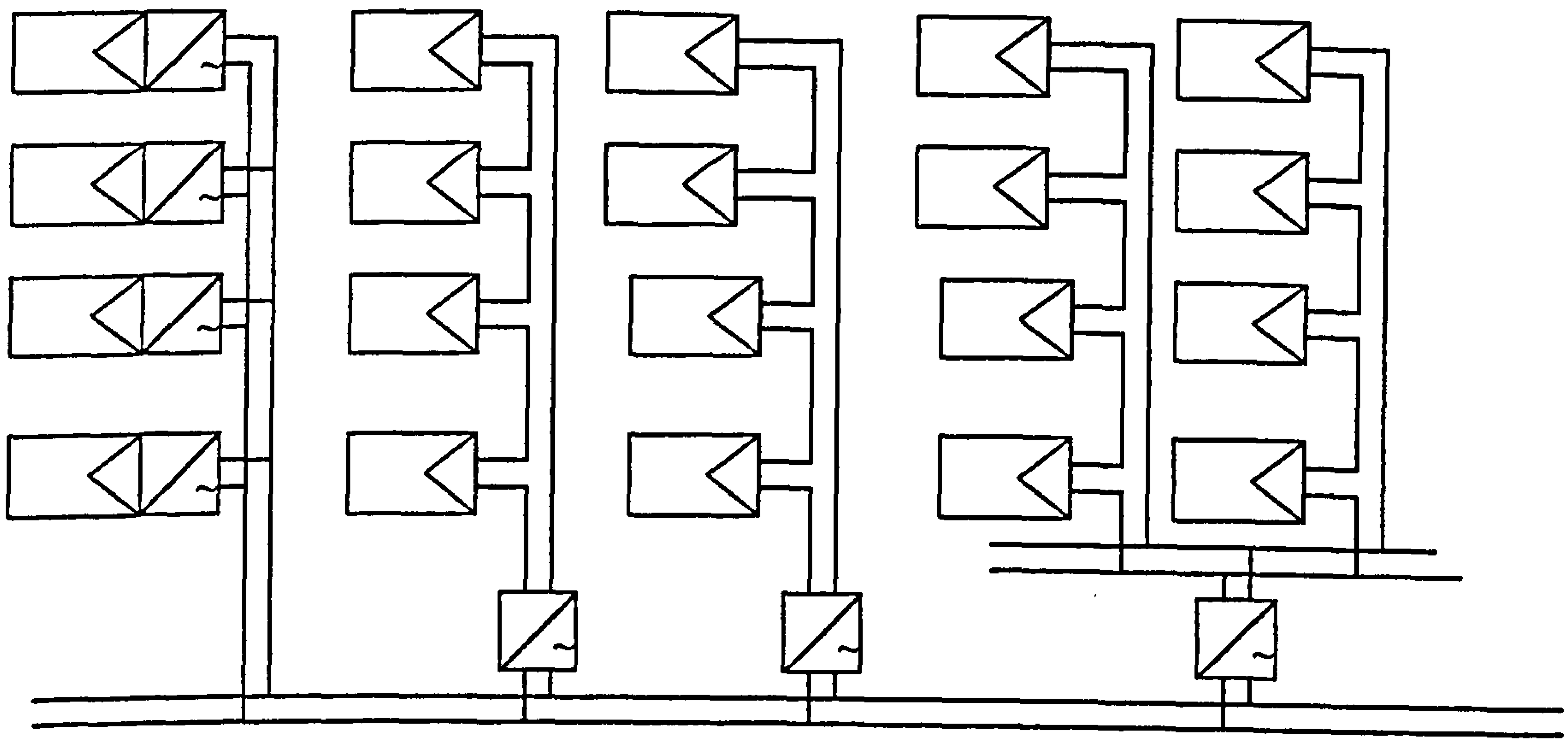


Figure 2.16: Basic Configuration of A PV System Supplying an AC Load.

Inverters are sets of automatic switches which provide polarity reversal to the DC current produced by the PV generator. Simple inverters therefore merely reverses the polarity of the DC current 50 times a second to form a square wave AC current. The square waveform has a good conversion efficiency, but its harmonic content is high and its output can overheat or damage some appliances. It therefore needs to be shaped. Like solar cells inverters have also evolved with the growing PV market, with the heavy magnetic transformers being replaced with high frequency semiconductor components. Inverters are increasingly becoming smaller and this has lead to the availability of a variety of them on the market as well as different configuration of the PV plant as shown in Figure 2.17.



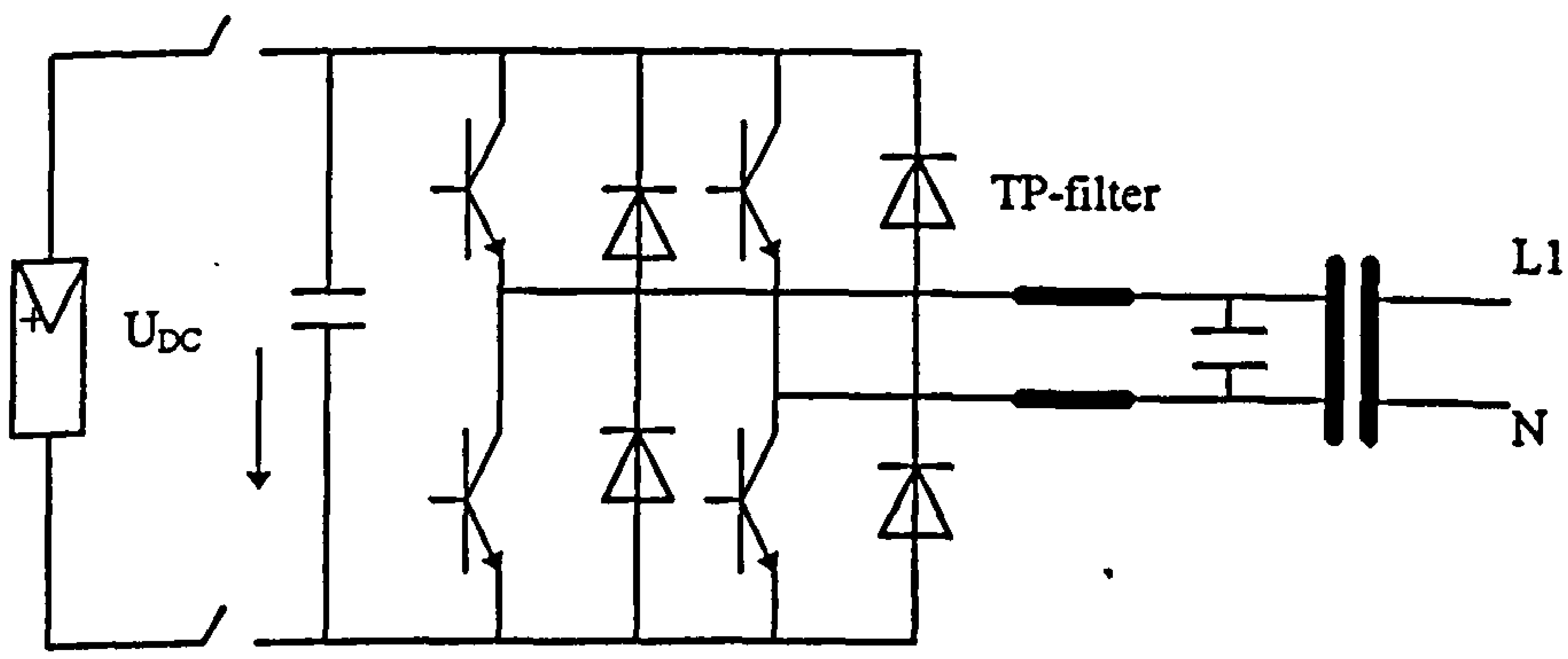
Module Integrated Inverter Configuration
String Oriented Inverters Configuration
Central Inverter Configuration

Figure 2.17: Different Inverter Connection Configurations

They are either stand alone or utility-interactive and they differ in their control circuitry.

2.3.5a Stand-Alone Applications Inverter

The correct timing of the 50/60 Hz AC power needed to operate AC appliances is done by an internal frequency generator. Therefore this inverter is also called a self-commutated inverter.



a. Inverter Structure

Figure 2.18a. Self-Commutated inverter [80]

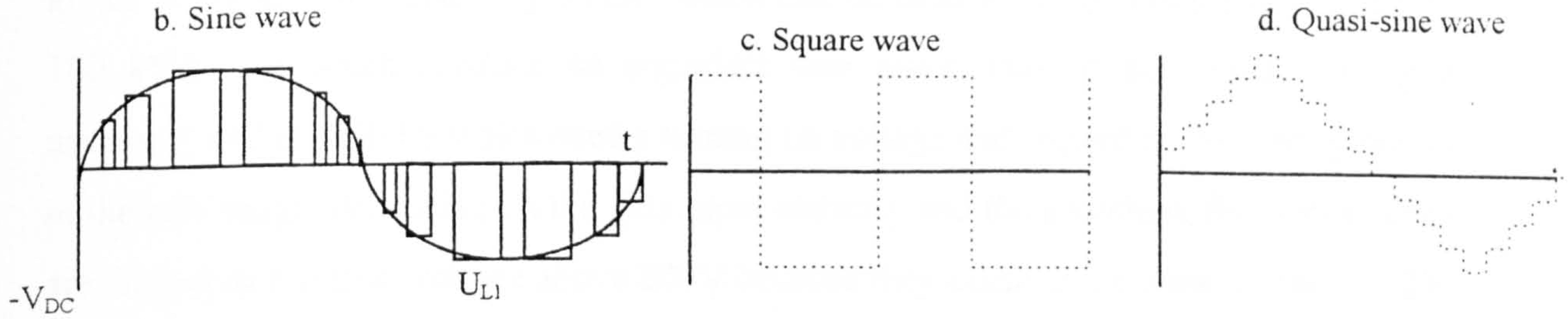


Figure 2.18b. Self-Commutated inverter Output

High conversion efficiencies are required in stand-alone systems. The shape of the output waveform is an indication of the quality of conversion, and a sine wave output is the highest quality. Sine wave inverters should always be chosen where possible for these systems. A control unit with pulse width modulation operates the semiconductor switches in Figure 18a, to produce the sine wave shown in Figure 18b. The low pass filter at the inverter output further improves the output signal. Sensitive loads require the output voltage to have a low harmonic content(with total harmonic distortion THD<3-5% recommended)[76], and this can be achieved by using higher switching frequencies, though this may raise switching losses and reduce efficiency. The square waveform (Figure 18c) is produced by a cheaper inverter.. The quasi-sine wave, Figure 18d, is produced by modern inverters. It is safe for many appliances and the inverter efficiencies range from 85% to 95%. The inverters use small amounts of power when they are in standby mode.

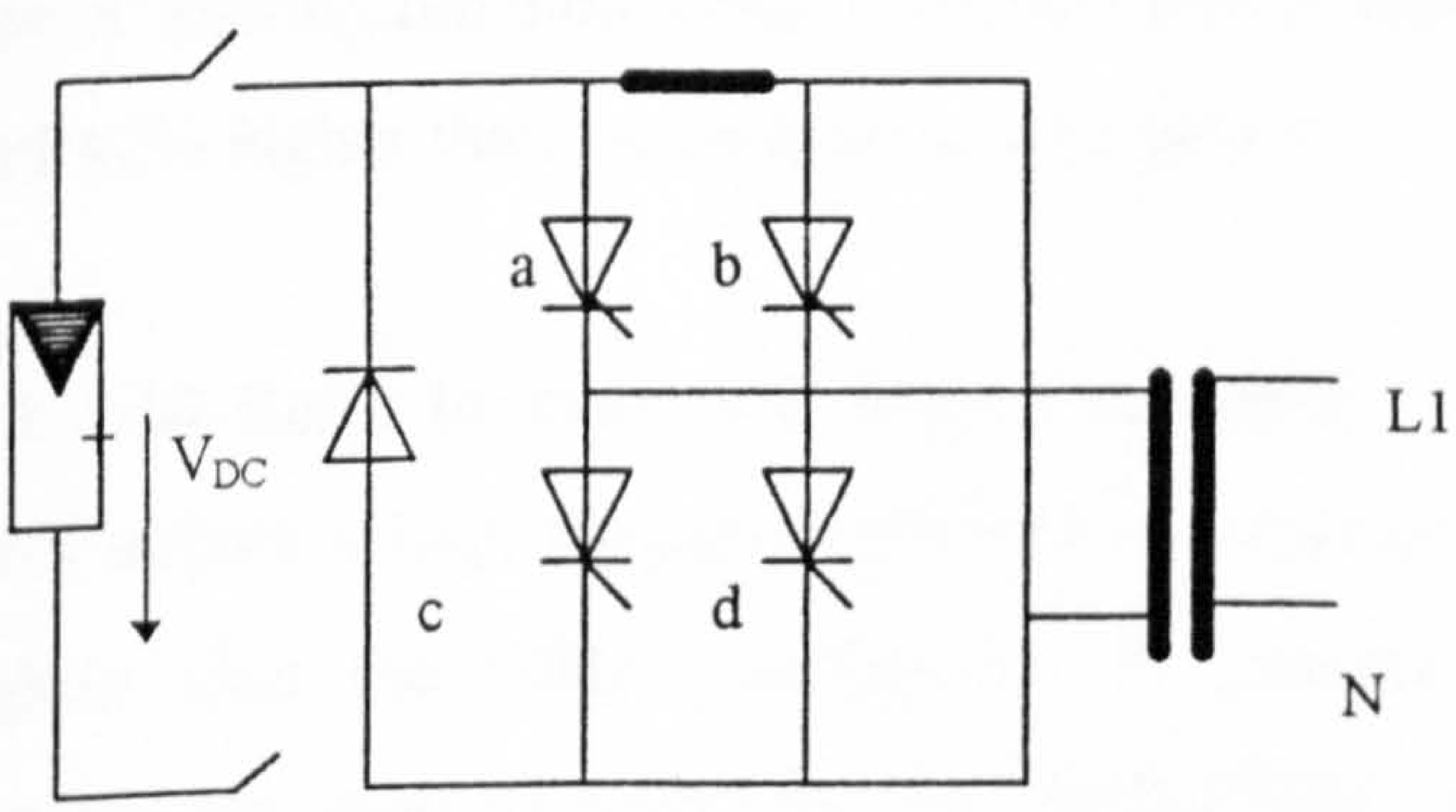
Recommended features of stand-alone inverters include i) an optimal size to handle motor-starting surge inrush currents and resultant short duration peak loads, while operating at maximum efficiency; ii) a surge capacity of ideally 2 to 4 times that of the nominal power; iii) low idling and no load losses; iv) output voltage regulation; v) low voltage disconnect; vi) a low harmonic content in the output; vii) a high efficiency and; viii) low audio and RF-noise production.

The semiconductor devices that can be used at the power stage include: i) MOS transistors which can be used up to the 5kVA power level and which have low switching losses at higher frequencies; ii) GTOs which can be used for large installations of up to 100 kVA, but which produce an imperfect sine wave, making additional filtering a necessity; and iii) IGBTS which need a turning on voltage and require a low driving power in the mW range depending on the gate input capacity and the switching frequency. They are limited to a system voltage above 200V because they cause an on-state-voltage of 2V, and they can be used for installations up to 200kVA.

2.3.5b Grid-Connected Inverters

These inverters give AC power output compatible with the requirements of the grid. It fully synchronises PV system output with the utility power by using the line-voltage frequency on the utility line as a control parameter. The waveform of this inverter should be an almost perfect sine wave. The static power inverter includes a possible means for controlling the entire PV system. This includes sensing the available array power and closing the grid side contactor to begin operating soon after sunrise and switching itself completely at night. The control logic also incorporates a protection system which detects abnormal operation conditions such as an earth fault on the PV system side; abnormal conditions on the utility side parameters such as line voltage, frequency and loss of a single phase; and inverter switch off when power stage is overheating. The inverter is protected against transient voltages by varistors on the DC and AC side. The inverter incorporates a MPPT which searches for a MPP every 1 to 3 minutes. The existence of varied size of PV systems which can be connected to he grid has resulted in a many types of grid-connected inverters. These include:

2.3.4bi. Line-Commutated Inverters[81]



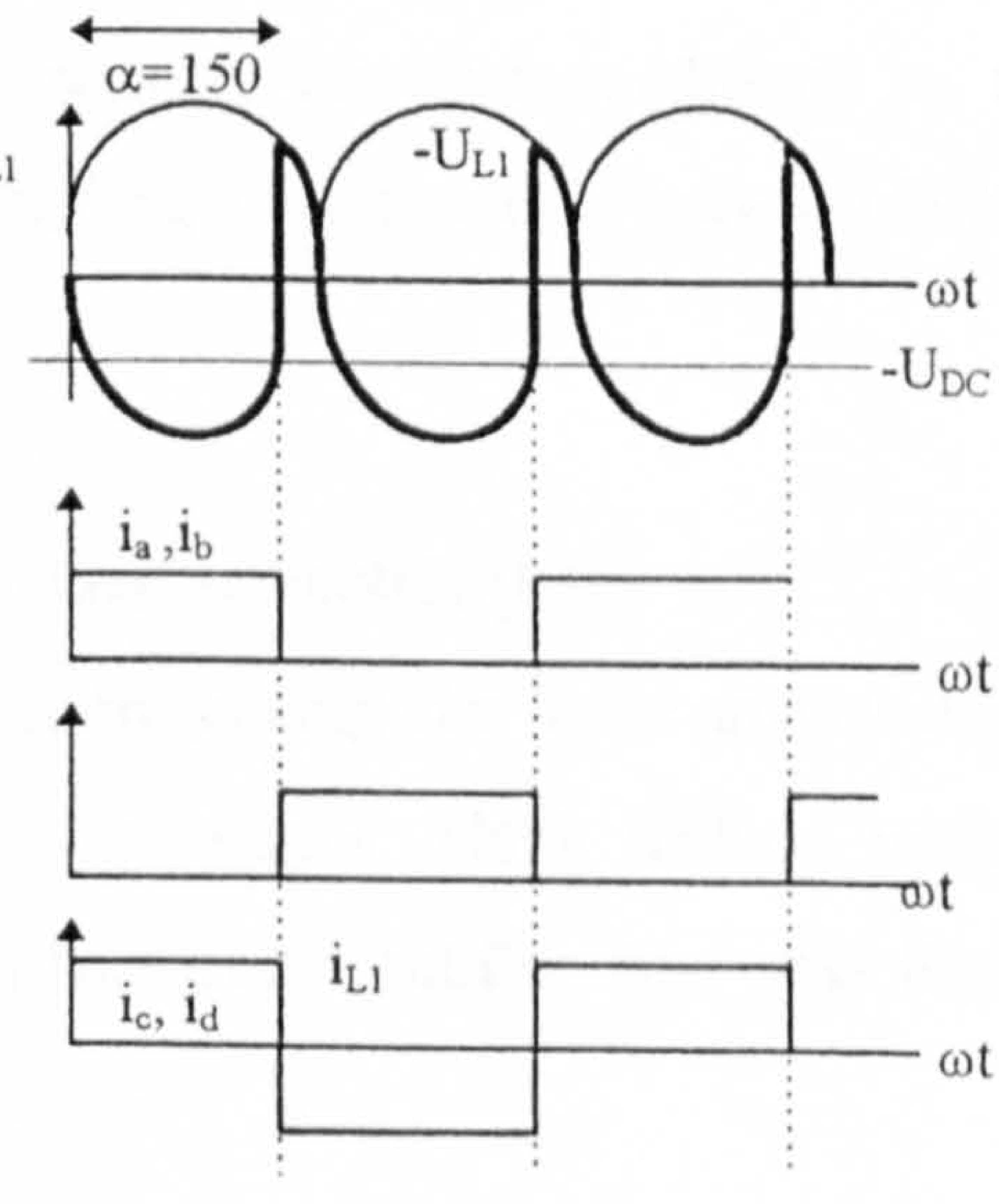


Figure 2.19: Line Commutated Inverter

These are traditionally commonly used for driving units of induction motors, and are equipped with thyristors for their power stage. They are modified to incorporate maximum power point tracking as well as the driver circuit to shift the firing angle from the rectifier mode ($0<\alpha<90°$) to the inverter mode ($90°<\alpha<180°$). 1.5kVA single phase units, <300kVA three-phase six-pulse units and 12 pulse inverters are available. They need a low impedance interface to the grid for commutation. Although their price is low they however can't be used if the maximum power is less than five times the rated inverter power, and they have a poor output with a high harmonic content which has to be filtered. Their power factor is also poor, being 0.6 to 0.7 inductive and requiring external phase shift equipment to meet the grid requirements which are normally better than 0.9. PWM inverter units with MOSFET transistors or an IGBT power stage are preferable for small systems less than 10kW in size.

2.3.4bii. Self-Commutated Inverter

This has the same form as that used for stand-alone applications in Figure 16. When connected to the grid they become line synchronised, and they can provide near unity power factor. They therefore do not load the grid with reactive power and eliminate the need for large power factor compensation. Ripple caused by the inverter operating in the switching mode, while using current pulses generated from a the PV array(DC source), reduces the system output because it makes the array unable to be operated at the maximum power point. The inverters are protected against overload conditions by a power limiting function which limits the power such that the array power is between 20% and 40% higher than the inverter output power.

2.3.4biii. Solar Inverter with High Frequency Transformer Section[82]

This utilises a high frequency(20kHz) transformer section making the latter smaller and lighter than the 50Hz transformers. It consists of five stages which include width modulation, high frequency inverter with PWM, high frequency rectifier, low pass filter and output stage. It uses many filters at the input and the output to eliminate the effect of radio frequency waves.

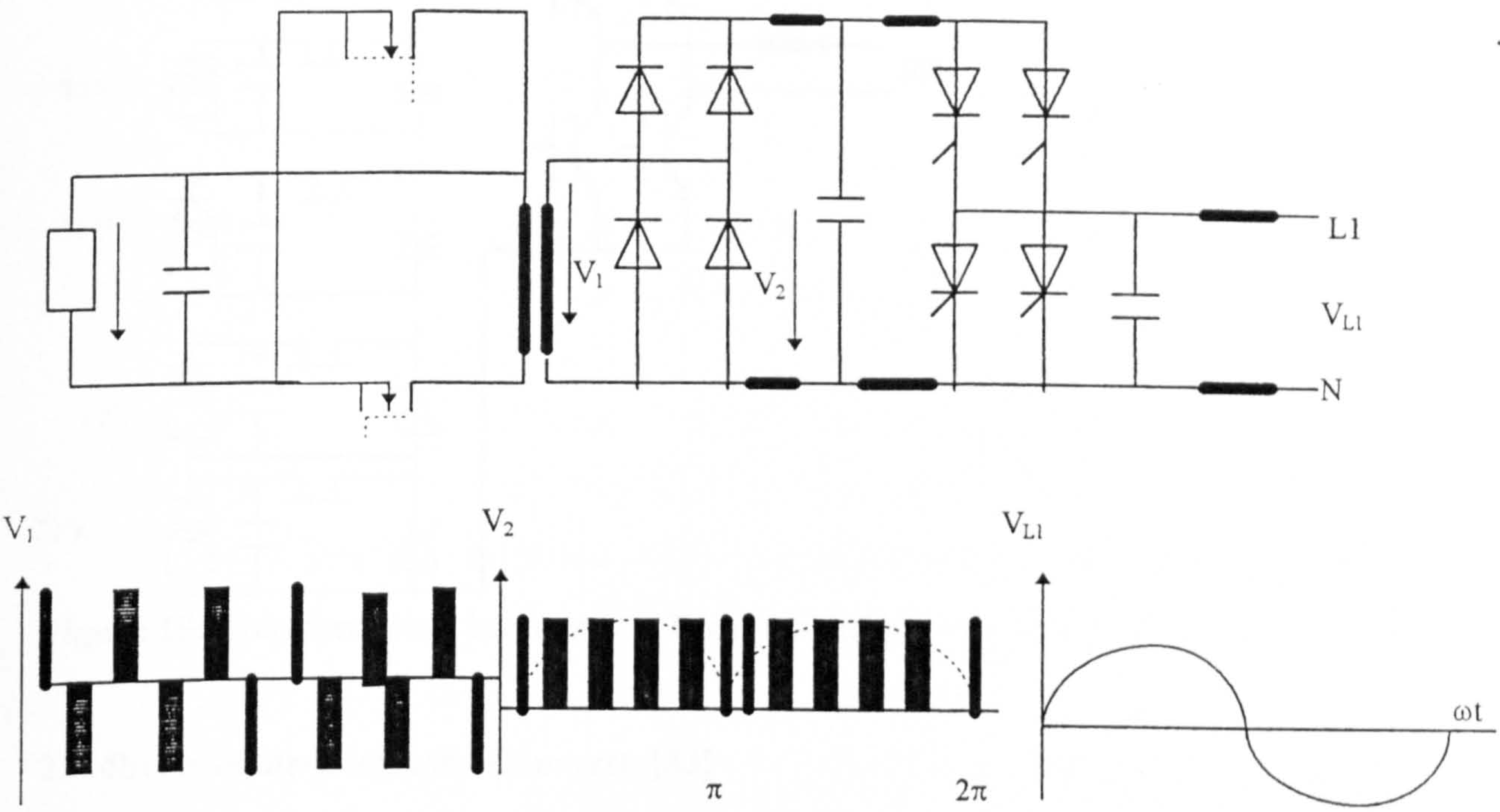


Figure 19: Inverter with High Frequency Section

2.3.4biv. Transformerless Inverter with Binary Switching Concept

This is specially designed for photovoltaic applications. It consists five different array stages, with the voltage values ordered to represent a binary system[80]. A sine wave generator triggers power switches to form a 230 VAC wave with 5-bit accuracy. The electronic switches connect a number of arrays which are necessary to follow the shape of the grid's voltage continuously. This inverter has high efficiency and exhibits low no load losses e.g. 7W in a 10 kW system. Its output has a low harmonic content and its small and light in weight. However, it requires much more complex wiring and light protection devices than other inverters. It also does not include a maximum power point tracker, and not all arrays are loaded with optimal voltage depending on the weather.

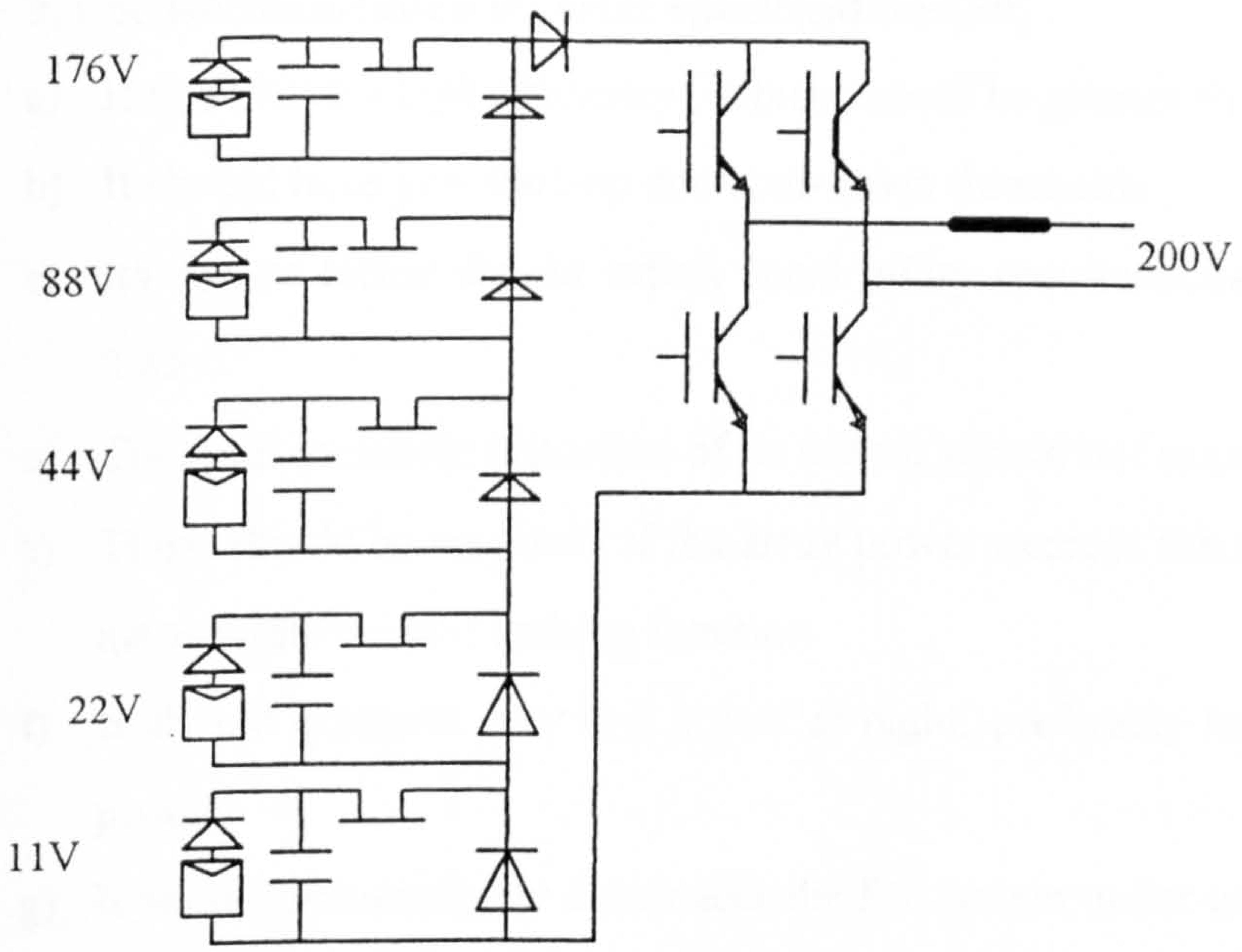


Figure 19: Transformerless Inverter with Binary Switching

2.3.4bv. Module-integrated Converter[83]

These generate floating AC power at module level. They extend the modular nature of PV systems in that they eliminate the need to centralise the conversion of energy into a few high power inverters, by integrating hard and soft switching techniques to achieve a 230V AC power level. They also eliminate a significant portion of cabling used at high DC voltage levels[90], reduce the risks of fire arcs and fire inherent in high DC voltage inverters. However, they need high reliability because their accessibility is limited, careful installation because they will be operating at non-optimal conditions and they need protection against islanding and earth leakage. Their block diagram is shown in Figure 19

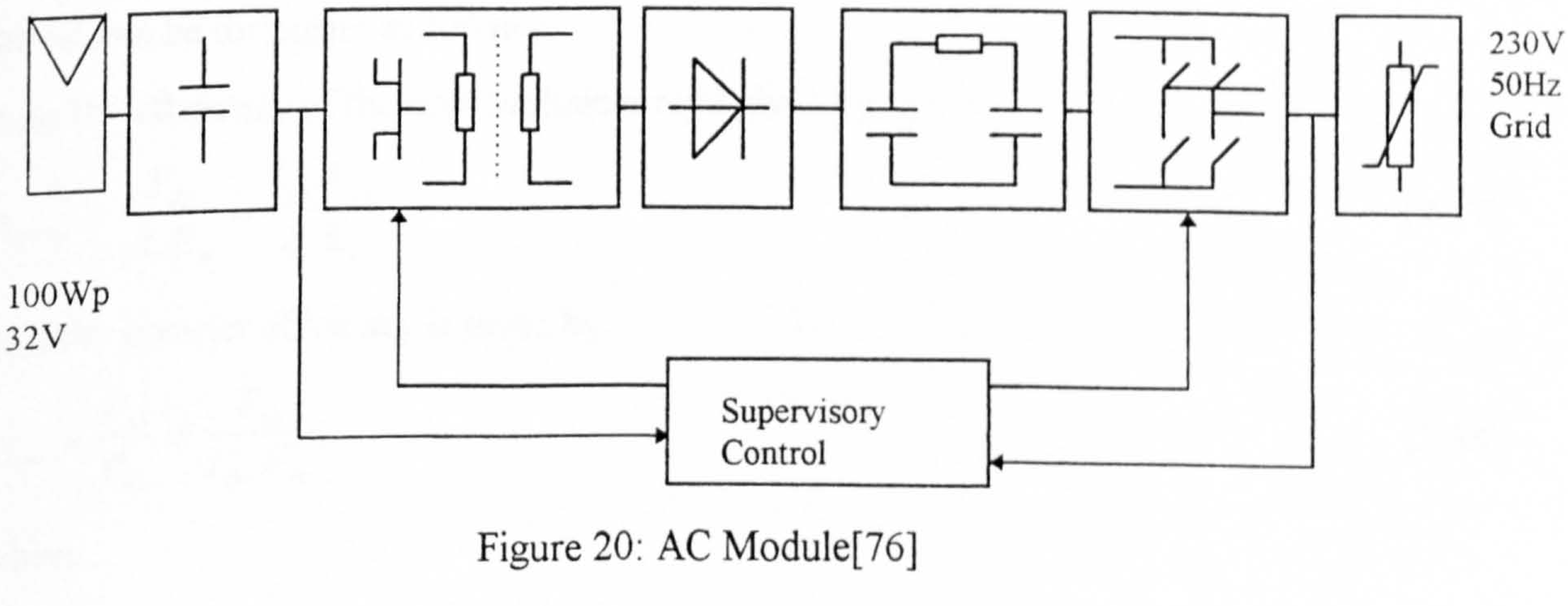


Figure 20: AC Module[76]

2.3.5c Recommended inverter specifications[80]

a) It must have a high efficiency , which should be greater than 92% .

b) It should have low start-up and shut-down thresholds

c) Its power factor should satisfy local utility requirements and should be higher than 0.85

d) The total harmonic distortion of its output should not exceed 3% at full power

e) There should be no power if the array power exceeds the rated value i.e. it should be a incorporate current limiting function.

f) It should consume very low power at night, preferably less than 0.5% of the nominal power.

g) It should automatically disconnect the PV system under utility fault conditions . These include voltage and frequency. It should automatically restart after fault is cleared.

h) The AC-ripple of the array voltage should be less than 3%.

i) The level of audible noise and RF noise on AC and DC side should be low.

j) A fan should be used for cooling.

k) There should be electric isolation between the DC and AC side and overvoltage protection on both sides

l) The inverter should exhibit higher availability .

2.3.6 PV System Models

The varied nature of inverters results in numerous models of their efficiency. This consequently results in numerous models for the total PV system output. However, a general model can be formulate as follows

η_{array} the efficiency of the photovoltaic array i given by

$$\eta_{array} = \frac{P_{dc}}{A.E_{e}} = \frac{I_{dc}.V_{dc}}{A.E_{e}} \tag{2.37}$$

η_{inv}, the inverter efficiency is given by

$$\eta_{inv} = \frac{P_{ac}}{P_{dc}} = \frac{P_{ac}}{I_{dc}.V_{dc}} \tag{2.38}$$

where

P_{dc}, the voltage produced by the array is given by[84]

$$P_{dc} = \rho K_{dc} P_{mo}\left[1-\beta_T (T-T_r)\right]\frac{E}{E_{eo}} \tag{2.39}$$

where

P_{mo} is the power output of a module at standard conditions

β is the temperature coefficient of the module at maximum power

K_{dc} is a factor given by

$$K_{dc} = mnn_d n_{mm} n_{fw} n_{bw} k_d \tag{2.40}$$

where

m and n are the number of strings and modules per string respectively

n_d is the diode factor

n_{mm} is the mismatch factor for series connected modules

n_{fw} is the wiring loss factor

k_d is loss factor for dust, dirt and power degradation

The total system efficiency is then given by

$$\eta_{tot} = \eta_{array}\eta_{inv} \tag{2.41}$$

2.4 Conclusion

The assessment of the state of the art of the photovoltaic technology has clearly shown that an energy generating technology need to integrate various disciplines in order to adapt to the needs of a growing market. The photovoltaic technology has successfully encompassed the disciplines of physics, electronic engineering, and supply-side electrical engineering. It has evolved into an adaptable technology which can be tailor made to suit the needs. The next phase is clearly taking into account more aspects of large scale demand-side electrical engineering, and integrating them with other disciplines such as building technology and mechanical engineering. The physical and numerical models developed so far in this field forms a springboard on which further research aimed at bringing the technology closer to demand side requirements can be formulated. It has also shown that there are factors which are site dependent and which merit that each area of the technology is researched within a local context.

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Chapter 3

Solar Energy Resource Estimation for Exemplar Buildings

3.1 Categorising The Building Stock in Harare City Centre

A building stock has to be categorised before the potential of any resource or technology on it can be estimated, because the stock is usually densely populated and diverse. Assessing the potential of each of the buildings would be time consuming and would not serve much purpose in terms of extrapolations and predictions. Therefore, proper representatives of the stock have to be identified after carefully studying the stock.

3.1.1 Methods of Categorisation

3.1.1a Traditional Method

Buildings have been traditionally categorised based on climate, building type and building size when studying energy use in a building stock[1]. Energy simulations based on typical building descriptions for each category have been used to analyse performance and results have been extrapolated to the actual building population[2]. The integration of the simulations of selected buildings with a database then led to a statistical basis on which inferences could be made in research work on the building stock. There is considerable economy in using the type, size and climate, but many other characteristics beside these three significantly affects energy use in a building. These include type of construction, amount of glazing, lighting power density, type of air-conditioning system and the operating regime of the building.

Categorising buildings for energy analysis purposes is therefore a multidimensional problem which requires care to be taken to avoid ending up with a large number of categories many of which might be insignificant[3]. Therefore, the building stock has to be subdivided into coherent categories with the objectives of providing as much resolution as possible relative to energy issues in a diverse building stock and to provide a concise set of simulations that would serve as an efficient tool for research into either the market characterisation of the buildings or the analysis of performances of systems installed on them.

3.1.1b Cluster Analysis

Cluster analysis, which is a statistical technique which groups observations based on similarities with respect to various energy related attributes is a non-traditional method that allows a general approach to analysing diverse populations and produces results that can be used in other researches on the populations[4]. When applied to building populations it removes the two-parameter efficiency limit of the traditional technique which usually leads to many categories[3]. It allows less important categories to be merged with those that are important to the intended analysis. The diversity inherent in the building population is not indicative of a random distribution. Thus, buildings with large floor areas tend to be taller than buildings with smaller floor areas, smaller buildings tend to be more climate sensitive than tall ones and buildings in one section of the city tend to be older than those in another section of the city. There also tends to be a strong relationships between physical and operational characteristics because of the interaction of technical, economic and historical factors[5]. Consequently, discarding the traditional approach of category definition actually results in natural clusters instead of matrices as shown in Figure 3.1

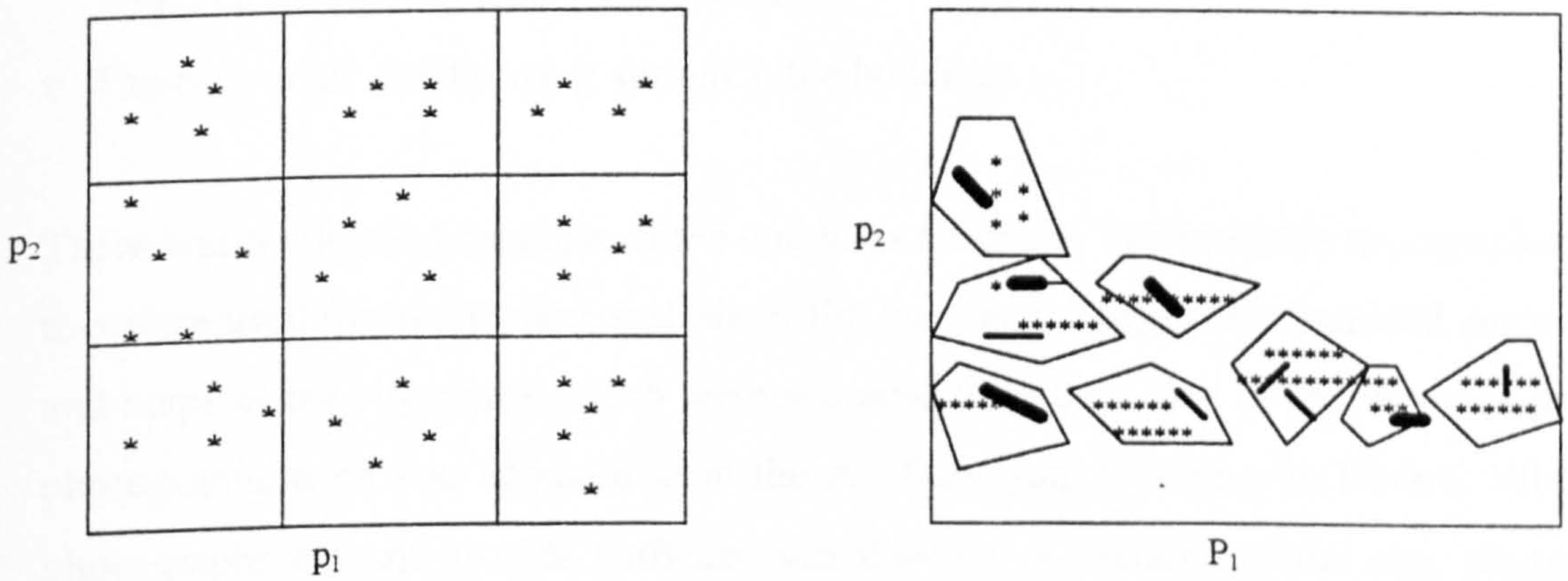


Figure3.1a: Traditional Matrix based categories **Figure 3.1b**: Cluster-based categories

These natural clusters can be placed on increasing levels of relevance to the research to be carried out. This then leads to a structure where hierarchical clusters are formed by clusters at one level combining to form clusters at a higher level[6]. Cluster analysis therefore results in categories defined only by variations due to plausible engineering bases.

3.1.2 Topographical Studies of The Benchmark City

A survey was carried out during a field visit to categorise the building stock in the city centre of Harare, the benchmark city for this study. The following factors were considered in the process:

i. type of construction, because of the importance of the effect of the building structure on the energy considerations to be made in the study

ii. age of building, since Harare is a city whose building picture is rapidly changing due to new constructions and demolition of old buildings

iii. climate will not have been an issue since the buildings to be considered are all located in Harare. However, a minor survey revealed that different opinions abound within the building engineering and architectural community as to how far the climate can be used to the best advantage in building design considerations.

iv. amount of glazing was also of prime importance since the major source of the cooling load seemed to be from solar gains. This was also important in the considerations of building-integrated photovoltaic systems because the trend to use expensive solar reflecting glass curtain walls meant a reasonable economic comparison could be made if the glass panels could be substituted with PV modules.

v. The type of air-conditioning system in the buildings

There was no detailed database of the buildings available. The available topographical tools were therefore used for preliminary analysis of the buildings. These tools included stereophotographs and maps of the city centre which were acquired from the office of the surveyor-general. Aerial photographs were also acquired from the Air Surveying Company in Harare. Where the aerial photographs did not provide sufficient visualisation of sections of the city, photographs were taken from the highest vantage points of the city. Close up photographs of the buildings in the city were also taken at street level to help in identifying characteristic features of the buildings and assist in making appropriate choices.

The following categories were therefore initially identified for the 60 buildings considered. Traditional techniques, of considering the age, size and type of buildings were used.

i. Pre-1970s buildings.

   In this category there were numerous low rise buildings, most of which were rapidly being destroyed and replaced by high rise buildings. There were also low-rise Colonial-Dutch style buildings and cathedrals. In this group only 10 buildings were considered to have potential for not being replaced by modern building in the foreseeable future.

ii. Early 1970s to Early1980s buildings

This category was dominated by high rise commercial buildings, which tended to have a rectangular aspect. There also existed in this group a significant number of hotels. This category had the largest number of buildings. 25 were identified to have potential for being considered for PV installation, based on preliminary observations.

iii. Recent buildings (solar reflecting glass curtain walls)

This category consisted mainly of high rise commercial buildings built in the late 1980s and 1990s, and which were dominated by solar reflecting glass curtain walls. Some were also departmental retail shops, of which 2 were prominent.. They provided the second biggest group with 15 buildings and it was the most rapidly growing.

iv. Recent buildings (with no solar reflecting glass curtain walls)

These buildings were also built in the late 1980s and 1990s, and they are predominantly high rise in nature. However, instead of having solar reflecting glass curtain walls they tend to have some form of shading features, mainly floor slabs which extend over the windows to form overhangs or they have reduced window area. This also, is a rapidly growing group although 10 buildings were identified in it.

3.1.3 Identifying Exemplar Buildings for Further Analysis

A collection exercise for detailed data was carried out which basically involved requesting permission to have access to the building plans from the building owners followed by a discussion with the architects where possible. Then a tour of the building was carried out with the maintenance engineers. Lastly, the building consultants involved during the construction of the building were contacted. This was not easy as the companies that were involved in the construction of the older buildings were usually no longer operating. The overriding factor proved to be the willingness or possibility of the responsible people at the said buildings to co-operate within the given time framework.

The cluster analysis method of categorising buildings described in 3.1.1b is a better approach for further categorisation of the buildings so that exemplars can be chosen. This was, however, not used because of the lack of a detailed database on the building stock in Harare. A more pragmatic approach was therefore used, using the limited data available and applying some aspects of cluster analysis relating to energy use in the buildings. These aspects included making observations based on similarities with respect to various energy related attributes in the buildings. This led to groups of increasing levels of relevance to the research on PV on buildings that was to be carried out. The combination of groups naturally led to some modifications of the initial categories. Therefore, by considering the use of the buildings, the energy use in the buildings and the effect of the building structure on the energy needs of the buildings the following categories were obtained

i. Low-rise Colonial-Dutch style buildings, usually used for administrative purposes by central and local authorities. They usually did not have centralised air-conditioning systems. Only 4 buildings: the townhouse, the parliament building, the main post office and the main telephone exchange fell into this category. This category was considered worthwhile studying for photovoltaic system installation because of the availability of a large roof area. This category of buildings, however, was not worked on further, after being identified, because though clearly distinct, it had a limited number of elements in the group, and most importantly it was found that the level of security consciousness in such buildings meant that no reliable data could be obtained on them.

ii. High-rise early 1970s buildings (with full mechanical air-conditioning)

    These exhibited a completely different intensity of energy use and building structure to buildings of the early 1980s which have full air-conditioning systems with which they had been grouped. The hotels fell into this category. They however were expected to have a long life through regular refurbishment and periodical replacement of their cladding systems.

iii. High-rise late 1970s and 1980s buildings (without full mechanical air-conditioning)

    These tended to have variable patterns of energy use because the lack of full air-conditioning systems, and a building structure which not adequately cater for thermal environmental control meant that individual air-conditioning units were utilised.

iv. High rise 1980s buildings (with full mechanical air-conditioning)

    These had the structure as those in category iii) but their thermal environment was controlled by centralised full air-conditioning systems.

v. Recent buildings (with full mechanical air-conditioning and solar reflecting glass curtain walls)

   These exhibited the highest energy usage and an expensive manipulation of the building structure in order to achieve good thermal environmental control.

vi. Recent buildings without full mechanical air-conditioning, but incorporating thermal environmental control features.

   These tended to rely more on the building structure in order to achieve good thermal environmental control. Mechanical air-conditioning in these buildings was only confined to specialist service areas such as computer rooms or retail outlets.

Detailed data in form floor and building services plan, and energy data were obtained for only 10 of the 60 buildings considered during categorisation. This combined with the considerations above resulted in the following buildings being chosen as exemplars for the categories ii) to vi).

i. An early 1970s 19-storey business hotel with full mechanical air-conditioning shown in Photograph A.1;

ii. A 20-storey government office building constructed in the late 1970s which has no mechanical air-conditioning shown in Photograph A.2;

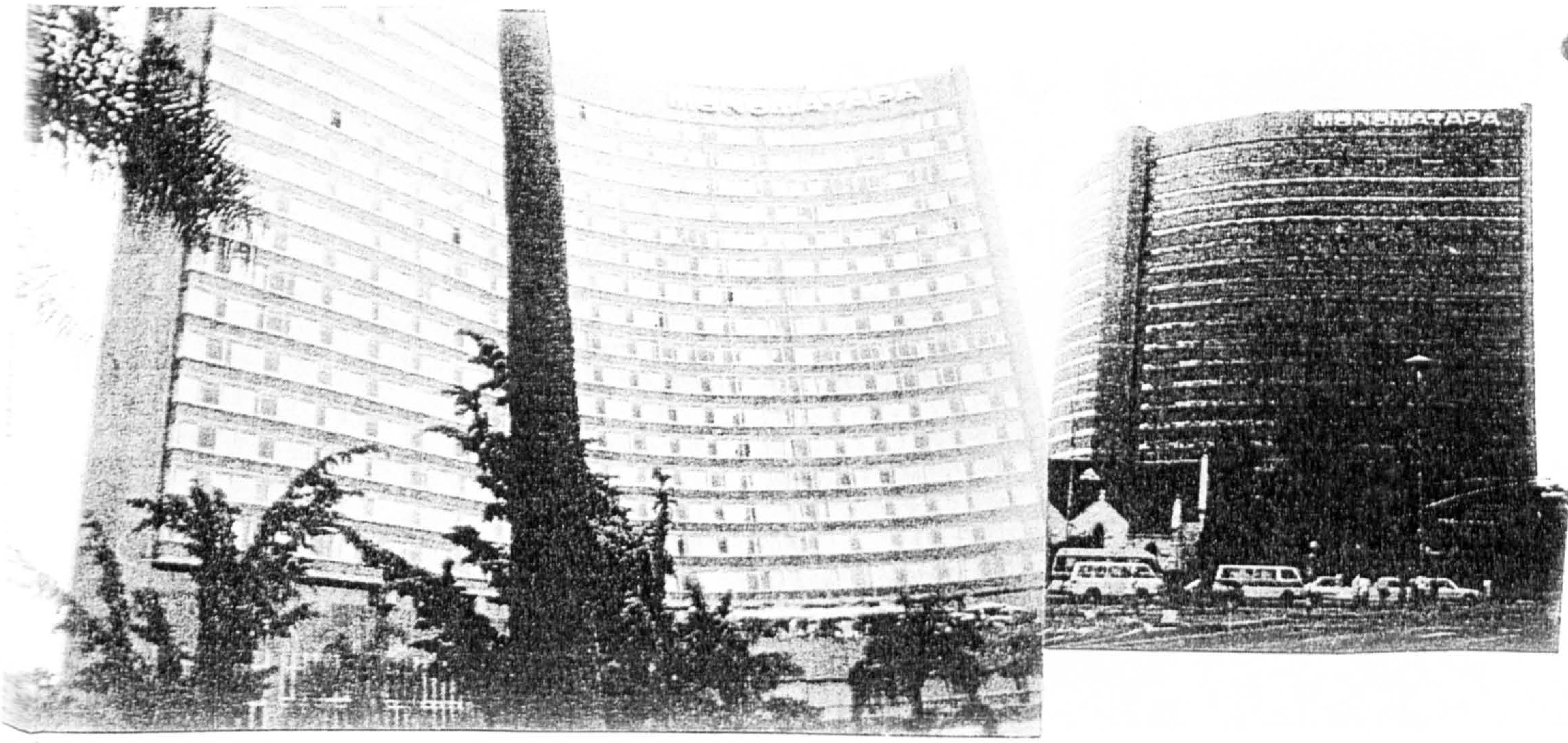
iii. A tenant occupied 17-storey commercial office building constructed in the mid-1980s which has full mechanical air-conditioning shown in Photograph A.3;

iv. A new prestigious institutional 26-storey commercial office building which has full mechanical air-conditioning shown in Photograph A.4

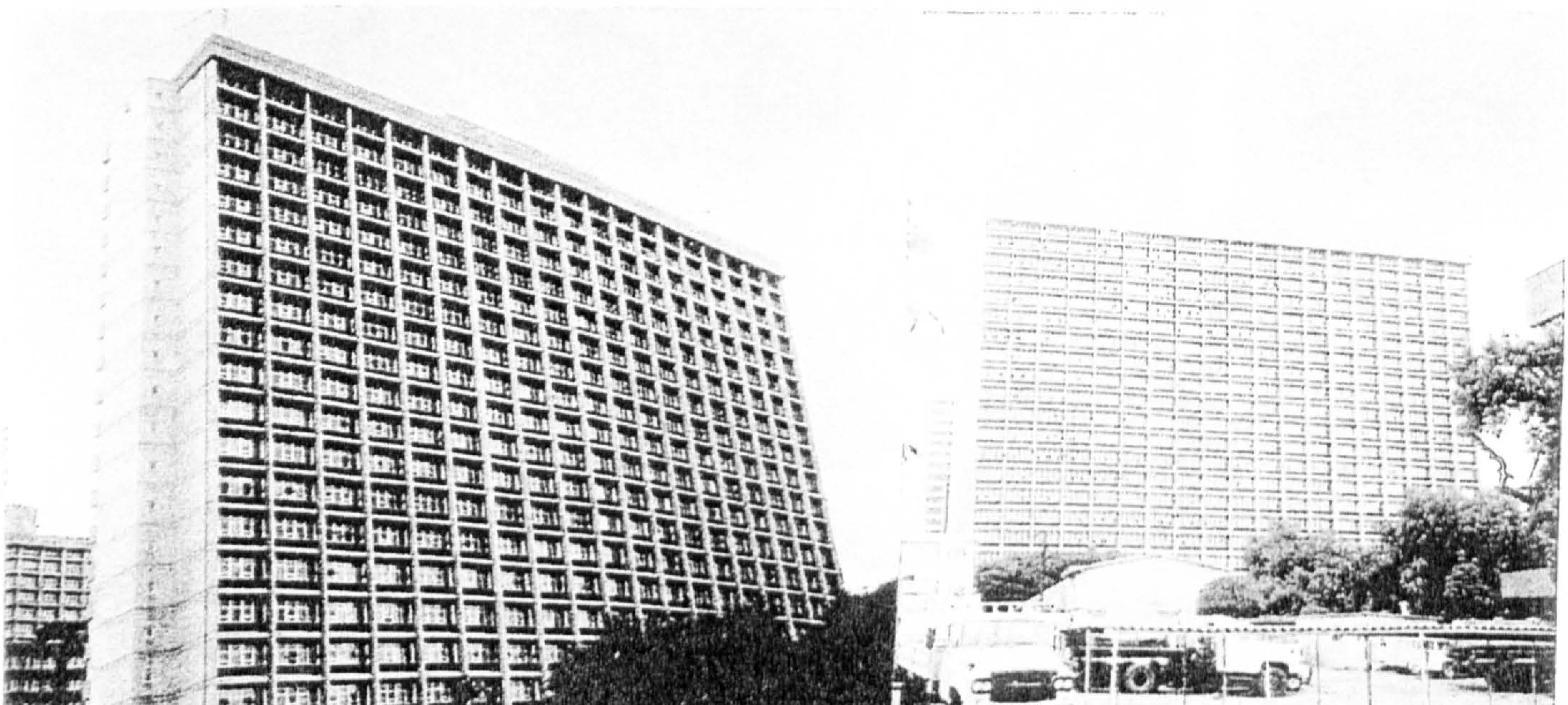
v. A new tenant occupied 8-storey commercial office building passively ventilated using the chimney effect and incorporating building massing and shading features shown in Photograph A.5.

3.1.4 Chronology of Categories

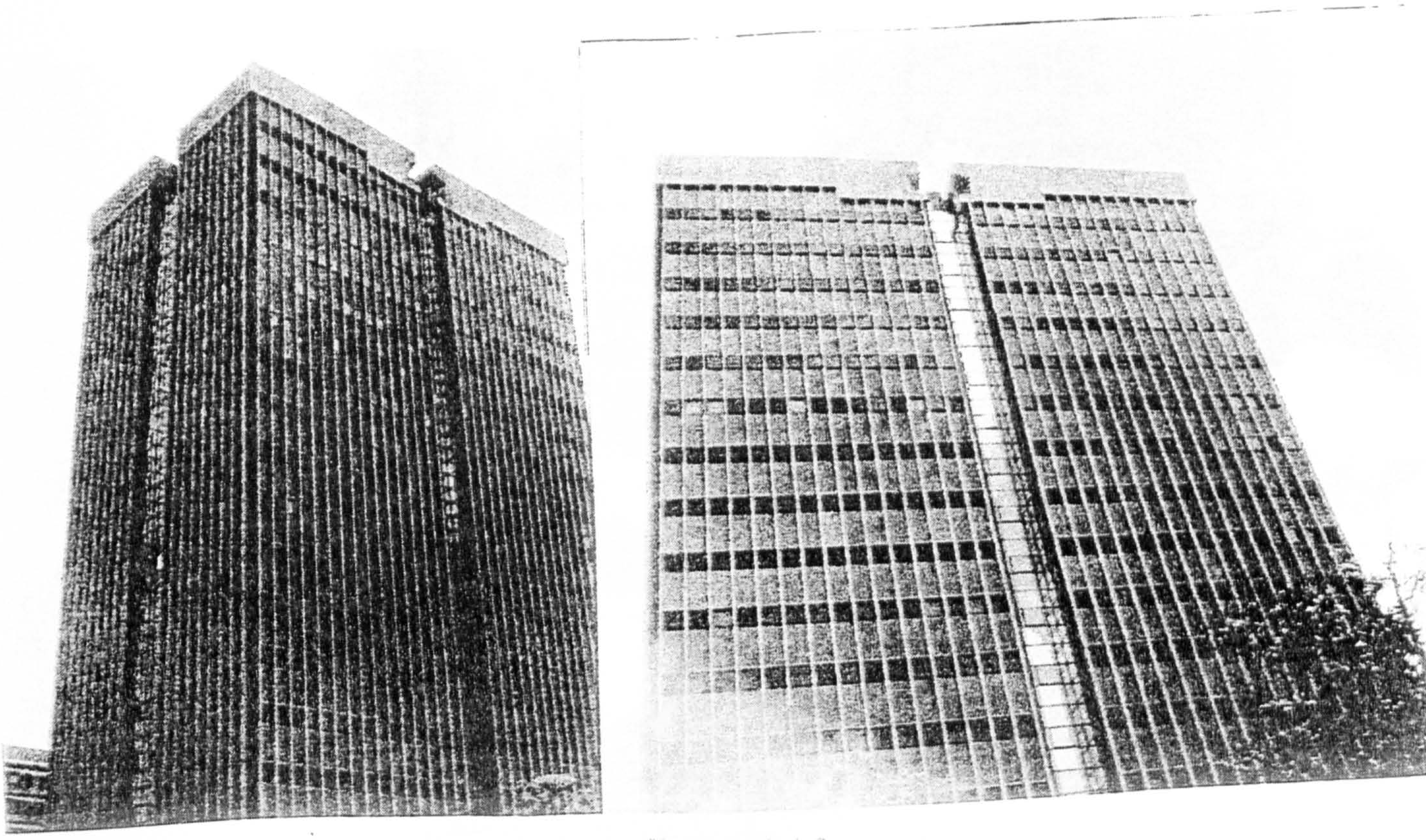
The hotel was chosen because hotels, although they tend to be situated in the city centre, have different operating schedules from other commercial buildings[7]. It also shows the effect the advent of full air-conditioning system had on building design. The government building was chosen because it is the most appropriate candidate for a building-integrated photovoltaics



Photograph A.1

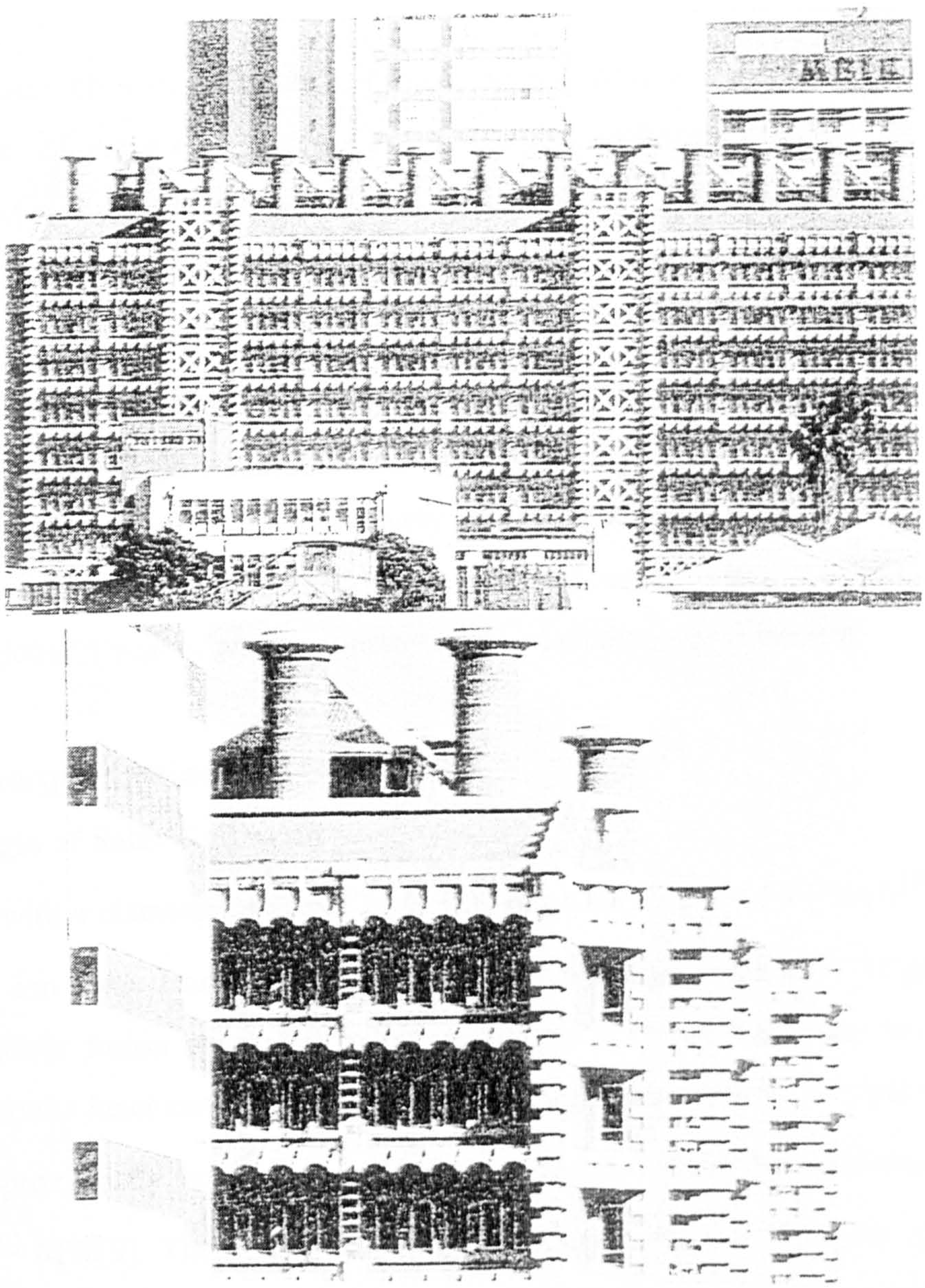


Photograph A.2

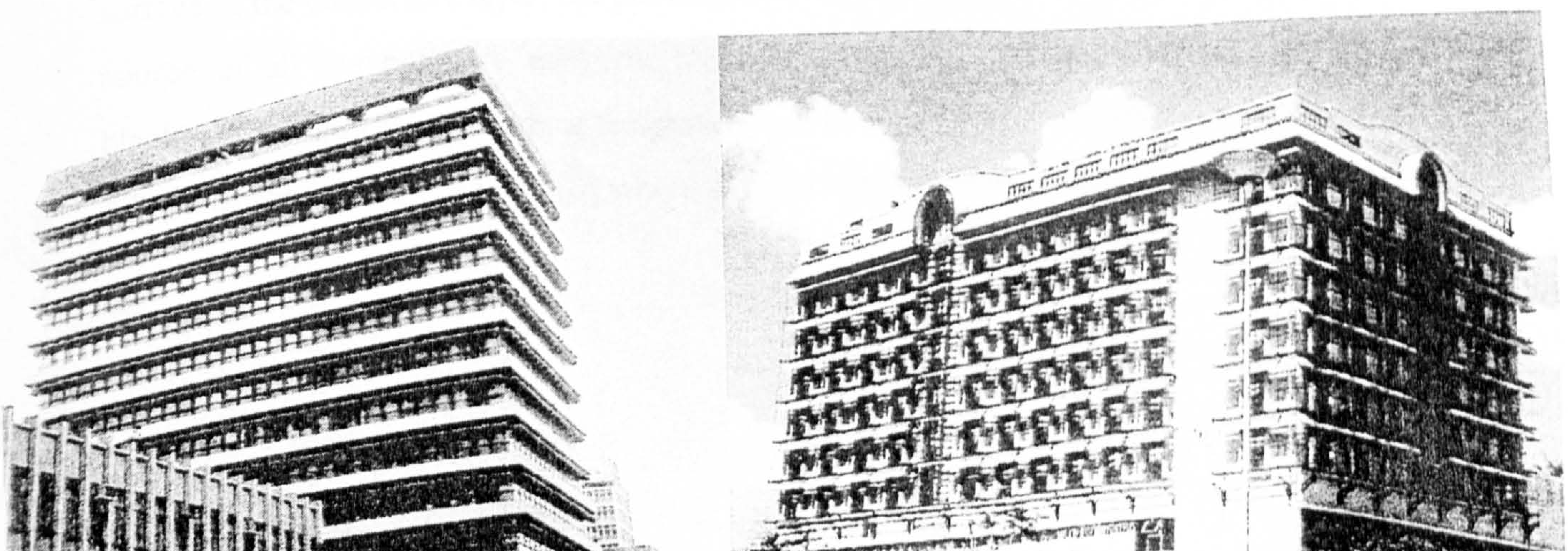


Photograph A.3

Photograph A.4



Photograph A.5



Photograph A.6

demonstration project, as such a project would give a powerful visual reflection of the commitment of the government to promoting that technology. It also reflects the change in attitude that occurred after the 1973 oil crisis whereby people became more energy conscious and tried to minimise energy use by doing away with full air-conditioning systems[8]. The tenant occupied 17-storey building reflects the increasing effect of the comfort demands of high profile tenants clashing with the energy conscious building engineer and architect. The prestigious office clearly shows that corporate statement and investor comfort demands had completely taken over from energy consciousness. The passively ventilated building shows that the gravity of the need for energy conservation within the local context had begun to be appreciated, and also shows the growing global appeal of energy consciousness as a corporate statement.

Solar Energy Physics and Geometry

3.2.1 Origin of Solar Radiation

The sun, with a diameter of about 1.39×10^6 km, a total mass of 1.99×10^{30} kg, and on average 1.50×10^8 km away from the earth, is the source of solar radiation. It generates energy in a thermonuclear fusion process in which hydrogen is transformed into helium. The process is confined to the inner core, occupying less than 2% of the sun's volume, yet containing 40% of its mass. Approximately 4×10^9 kg of material is converted to energy each second, generating about 3.70×10^{20} MW[9]. The generated energy is radiated outward from the centre to a distance of about 70% of sun's radius and it is then brought to the sun's surface by convection. The outer surface of the convective layer, the photosphere, with a temperature of about 6000K is the direct source of all the radiative emission from the sun. The sun therefore radiates energy like blackbody radiator with a surface temperature of 6000K, over a wavelength spectrum from 300-470nm as shown in Figure 3.2[10] where extraterrestrial and terrestrial spectra are compared.

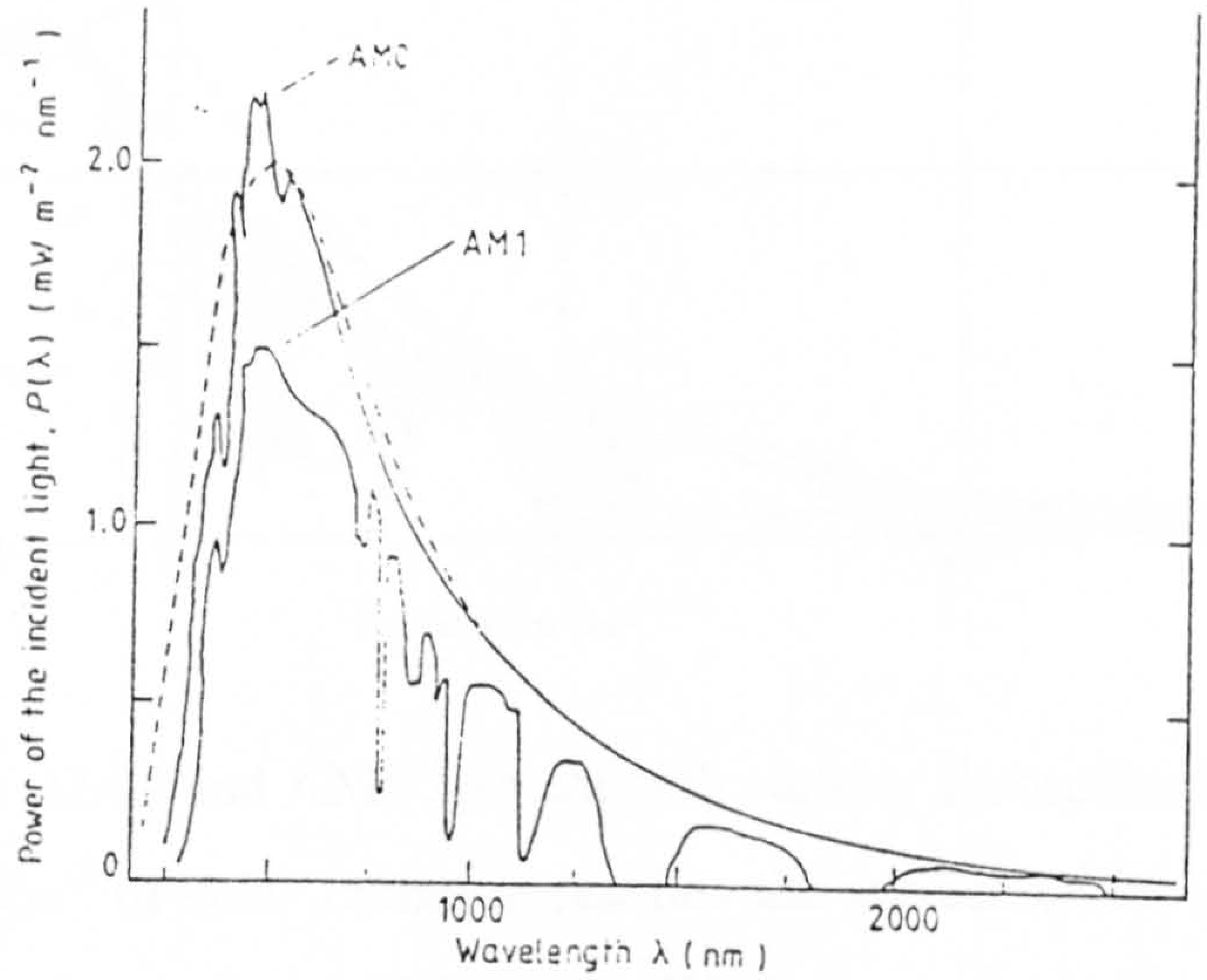


Figure 3.2: Extraterrestrial and Terrestrial Radiation Spectra

A maximum of 2200Wm^{-2} solar intensity at 470nm is incident on the top of the atmosphere, though the average total has recently been found to be 1370Wm^{-2}[11]. Early measurements resulted in a mean value of 1353 kW/m^{2}[12] being widely used. The elliptical nature of the earth makes the solar constant vary by about ±3.35% from a maximum value of 1416Wm^{-2} in January to a minimum of 1323Wm^{-2} in July. The fluctuations in the radiant output of the sun also accounts for about ±1.5% variation[13] The intensity and spectral distribution of the radiation incident on the earth is dependent on the nature of and the pathlength through the atmosphere. The most important effects are due to the water content, the thickness of the ozone layer, cloudy cover, haze and scattering. These effects are accounted for by the zenith angle which is location and time dependent. The term air mass has been introduced to represent the relative thickness. The air mass is defined as the path traversed by the radiation expressed as multiples of the path traversed at sea level with the sun directly overhead. The relative air mass, m_r, is defined as the secant of the zenith angle and solar spectra for specific purpose have been labelled according to it. The most widely used spectra have already been described in Section 2.1.4. AMO and AM2, the spectrum of the radiation incident on the earth's surface, as well as the various atmospheric absorption bands are shown in Figure 3.3.

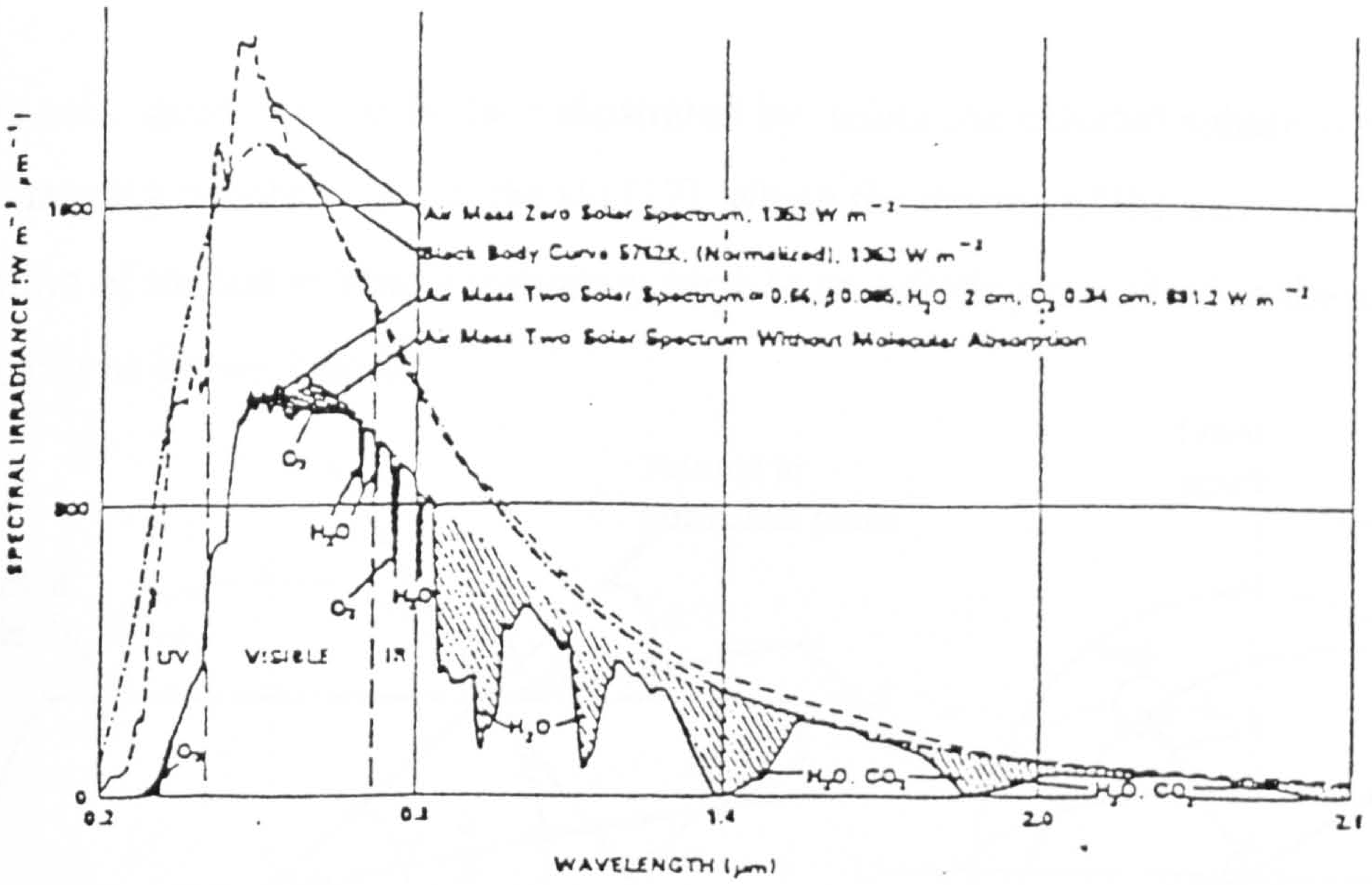


Figure 3.3: AMO and AM2 Spectra with various absorption bands [14]

Only about 1025Wm^{-2} of solar radiation reaches the surface of the earth, when the sky is clear and the sun is directly overhead. Of this 945Wm^{-2} is received directly from the sun, while the remaining portion is diffuse radiation received indirectly from the sun.

3.2.2 Solar Geometry

The earth revolves about an axis inclined at an angle of approximately 23.45^0 to the plane containing the orbit in which it rotates around the sun. This declination angle, δ, changes incessantly between -23.45 and +23.45. Spencer[15] has given a general expression for δ as

$$\delta = \frac{\pi}{180}\Big(0.006918 - 0.39912\cos d_n + 0.070257\sin d_n - 0.006758\cos(2d_n) + 0.000907\sin(2d_n) - 0.002697\cos(3d_n) + 0.00148\sin(3d_n)\Big) \qquad (3.1)$$

where the day angle is given by $d_n = \frac{2\pi}{365}(n_d - 1)$

and the day number of the year by n_d.

The declination angle has been alternatively given as[16]

$$\delta = 23.45\sin\left[\frac{360}{365}(284 + N)\right] \qquad (3.2)$$

where N is the year day number of the

The solar geometry can be best illustrated by using the celestial sphere which is a classical way of mapping remote points in the sky[17], where the motion of the earth is represented by the motion of the sun around a stationary earth in an ecliptic plane tilted at the angle δ to the celestial equator as shown below:

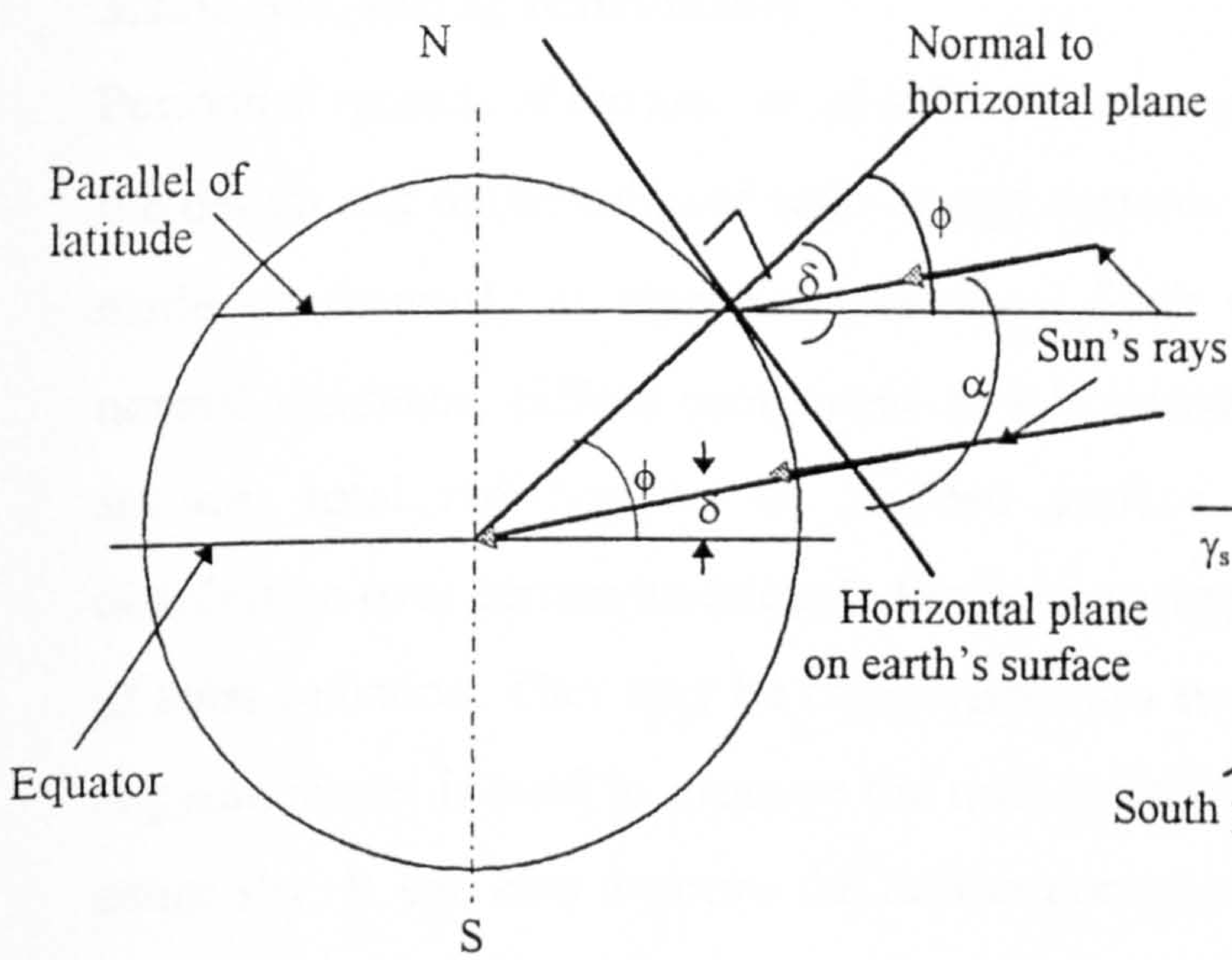


Figure 3.4a: Plane Through The Earth

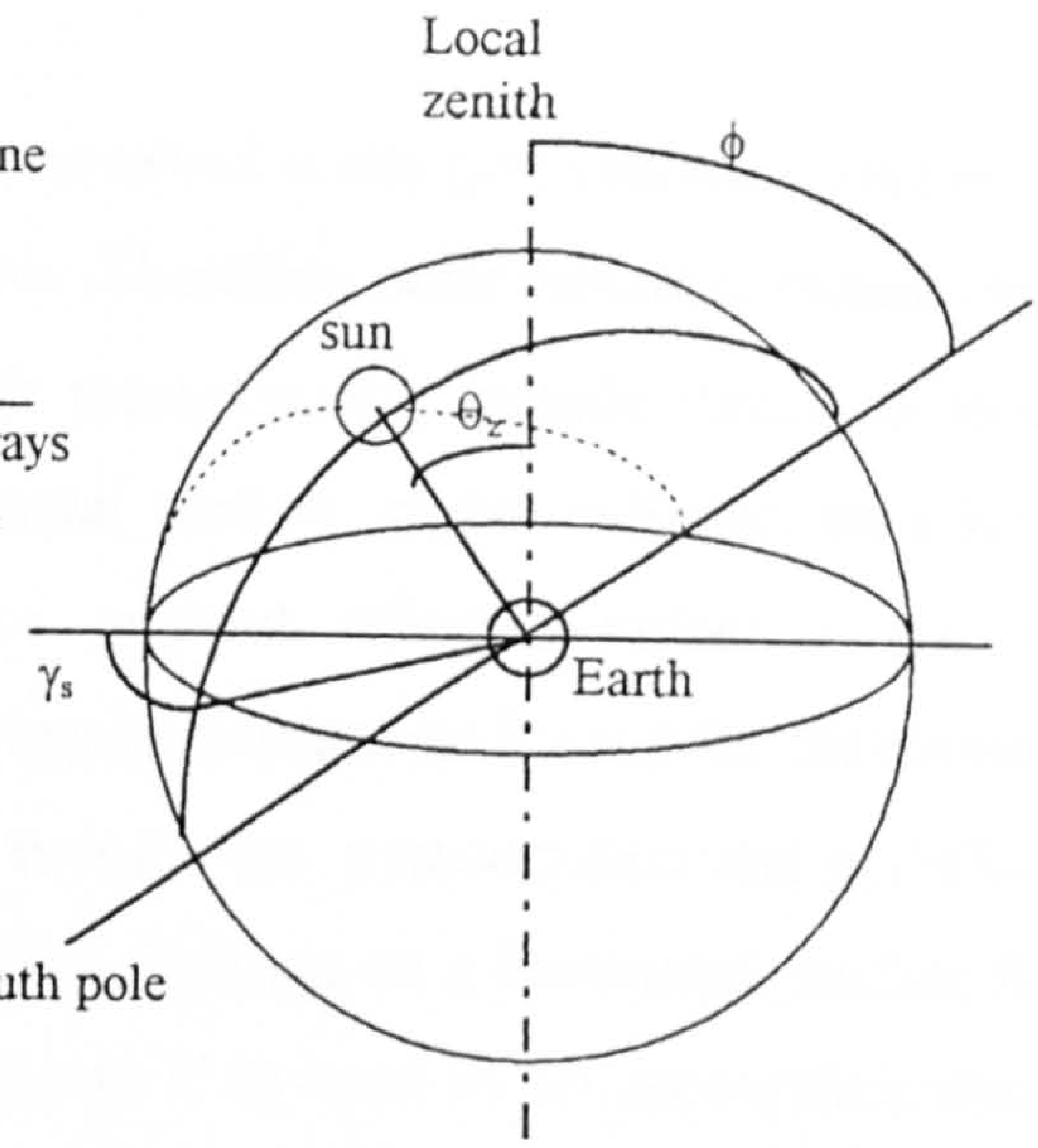


Figure 3.4b: Celestial Sphere

The altitude of the sun α can be represented by its compliment, the zenith angle, θ_z derived by vector calculus[18] as

$$\cos\theta_z = \sin\alpha = \sin\delta\sin\phi + \cos\delta\cos\phi\cos\omega \tag{3.3}$$

while the angle between the horizontal component of the sun and the polar axis, the azimuth angle, γ_s is given by

$$\cos\gamma_s = \frac{\sin\alpha\sin\phi - \sin\delta}{\cos\delta\cos\phi\cos\omega} \tag{3.4}$$

where ϕ is the latitude of the location, and ω is the hour angle given by

$$\omega = \frac{360^\circ}{24}\left|12 - t_s\right| \tag{3.6}$$

where t_s is the solar time

Equations (3.3) and (3.4) define the position of the sun relative to the horizontal surface. For an inclined surface the orientation is defined by the zenith angle or slope β and azimuth γ_s. The solar incidence angle is then given by[19]

$$\cos\theta = \sin\delta\sin\phi\cos\beta - \sin\delta\cos\theta_z\sin\beta\cos\gamma_s + \cos\delta\cos\phi\cos\beta\cos\omega + \cos\delta\sin\phi\sin\beta\cos\gamma_s\cos\omega + \cos\delta\sin\gamma_s\sin\omega\sin\beta \quad (3.7)$$

3.2.3 Solar Radiation Measurement

3.2.3a Measuring Instruments

Periodical records of the amount of solar radiation received at any given location are essential for the design and optimisation of solar energy systems. Therefore, solar radiation measurements are made continuously at monitoring stations. Such measurements include direct component at normal incidence, diffuse component at a horizontal surface, global radiation on a horizontal surface, total radiation on an inclined surface, ground reflected radiation, and spectral distribution over certain wavelength bands. A variety of instruments is used for the measurement of solar radiation. They may be categorised into two groups: pyranometers and pyrheliometers. A pyranometer is used to measure the total radiation, incident on a horizontal surface from the entire sky. It can also measure the diffuse component if covered by an appropriate shade. The operation of most pyranometers is based on measurement of temperature difference between black and white elements using a thermopile[20]. Low cost pyranometers, with low sensitivity to tilt and temperature, are built with silicon photovoltaic cells and hence they are called silicon pyranometers[21]. A pyrheliometer measures the intensity of the direct solar radiation at normal incidence. Most pyrheliometers used for routine measurements operate on the thermopile effect so are similar to pyranometers in this respect. They differ in that they must mechanically follow the sun to measure only the direct sunlight and avoid the diffuse component. In practice, direct solar radiation is measured by attaching the instrument to an electrically driven equatorial suntracking mount. The diffuse component is avoided by installing a collimator tube over the sensor with a circular cone angle of about 5°[22].

Apart from the direct solar radiation records, there may be records of sunshine hours and approximate cloud cover for the location under interest. Nowadays the tendency is to acquire a whole measurement system with all the sensors for measuring the various meteorological parameters. The sensors are equipped with the signal conditioning circuitry to enable them to be interfaced with a datalogger[23] with enough memory to keep long term data which can be accessed by a computer and used for further analysis.

3.2.3b Sources of Measurement Error

Solar radiation measuring instruments are not generally considered to be very accurate and calibrating them is an essential part of using them. Accurate solar radiation measurements strongly depend on several major variables, all of which in some way are functions of the limiting characteristics of the instrument. The important variables are sensitivity, stability, temperature coefficient, spectral selectivity, linearity, time constant, cosine response, and azimuth response. Based on the values of the parameters, instruments can be classified to be of first class, second class or third class[24].

3.3 Solar Radiation Estimation Algorithms

The design of photovoltaic systems is highly dependent on the availability and accuracy of insolation data[25]. It also requires additional knowledge of ambient temperature and wind speed. As the measurement of solar energy requires expensive equipment which is costly to operate as well as maintain, such measurements are undertaken at only a limited number of stations. Empirical formulae are therefore resorted to for estimation of radiation, for locations at which no measurements are available. Various climatological parameters have been used in developing empirical relations as substitutes for the direct measurement. Therefore, three basic problems can be clearly identified as most relevant when estimating the components of solar radiation incident on a surface:

i. availability of reliable data sets

ii. evaluation of the global radiation from other meteorological variables such as amount of sunshine, cloud cover, relative humidity, etc.

iii. conversion of the horizontal components of the radiation into equivalent inclined components.

Numerous models have been developed for estimating insolation data based on the available hourly data measured directly [26]. Solar radiation is also dependent on the location of a place and other features in the locality of the place such as buildings and trees[27]

3.3.1 Formulating Model Comparison Methods

Most solar energy receivers are tilted at some angle with respect to the horizontal [28] either through the need to optimise the amount of solar energy captured by positioning the receiver at an angle close to the latitude of the place or through the restrictions of the surface on which the receiver is mounted. Lack of measured tilted surface radiation data has meant that models have to be employed to estimate this radiation from the measured horizontal radiation. This is achieved by first dividing the global horizontal radiation into its beam and diffuse components through measurement or through hourly diffuse fraction correlations [29, 30]. The available isotropic and anisotropic hourly tilted surface radiation models can be best analysed in terms of the utilisable energy, which is the energy beyond a certain threshold level.[31] The difference between the measured utilisable energy and the predicted one for various slope/azimuth orientations and critical radiation levels give an indication of the performance of the models. Root mean square and mean bias differences statistics are usually used to quantify the tilted surface model performance[32]. While large databases of tilted surface radiation have been used to compare measured data and data predicted by several models[33], it has been suggested that additionally using various reference systems to explore the effects on the auxiliary energy required for a given system gives the best indication of model performance for solar energy system simulation[34]. However, these methods of model comparison have been found to produce results which are difficult to extend to other solar energy systems. On the other hand utilisability has been found to be useful in predicting the performance of both active and passive solar energy systems, because it is independent of a particular system[35].

All data sets tend to contain missing data or data which exceed the physical limits of the quantity they represent. In the case of solar data this involves negative values, diffuse fractions greater than 1, or beam radiation exceeding the extraterrestrial beam radiation[36]. Deviating data can be identified by imposing tolerance limits. There also exists an uncertainty associated with radiation measurements at large incidence angles. Therefore where the zenith angle is 80°, the related data tend to be eliminated.

3.3.2 Tilted Surface Radiation Models

The total radiation on a tilted surface is composed of three elements: beam, diffuse, and ground reflected. The angular correction is straightforward for the beam component but that of the diffuse component depends on its distribution over the sky. Diffuse solar radiation is difficult to model because of its generally unknown spatial distribution and time dependence. The distribution depends particularly on cloud cover and also on the spatial distribution and amounts of other atmospheric components. This has led to several models being proposed to estimate the radiation on a tilted surface. It has been said to be the largest potential source of computational error[37]. The five common tilted surface models are:

i. isotropic model
ii. Hay and Davies model
iii. Perez Model
iv. Perez2 Model
v. Klucher Model

The beam radiation on a tilted surface, of slope β, is modelled with a geometric factor R_b, [38] which is the ratio of the hourly (or instantaneous) beam radiation on a tilted surface, $I_{b,T}$, to the hourly beam radiation on a horizontal surface, I_b and it is given by

$$R_b = \frac{I_{b,T}}{I_b} = \frac{\cos\theta}{\cos\theta_z}$$

$$= \frac{\cos(\phi-\beta)\cos(\delta)\cos(\omega_s)+\omega_s\sin(\phi-\beta)\sin(\delta)}{\cos(\phi)\cos(\delta)\sin(\omega_s)+\omega_s\sin(\phi)\sin(\delta)} \tag{3.9}$$

Ground reflected radiation can be assumed to be purely diffuse[39] for practical purposes and is given by

$$I_{g,T} = I\rho_g\frac{(1-\cos\beta)}{2} \tag{3.10}$$

where ρ_g is the ground reflectance and $\frac{(1-\cos\beta)}{2}$ is a view factor.

Assuming that most of the diffuse radiation comes from an apparent origin near the sun, then the geometric factor R_b can also be used for the diffuse component The total radiation incident on the surface is then

$$I_T = R_b \, (I_b + I_d) \tag{3.11}$$

The above equation gives a good estimation under clear sky conditions and this limits its usefulness. A better assumption is that the diffuse component is uniformly distributed over the sky. This is a reasonable assumption when there is uniform cloud cover or when conditions are very hazy. Then the diffuse radiation will be independent of collector orientation the total radiation will then be

$$I_T = R_b \, I_b + I_d \tag{3.12}$$

Three diffuse subcomponents are used to approximate its anisotropic behaviour. These are circumsolar radiation , horizon brightening and the isotropic diffuse radiation.

The isotropic model[40] is the simplest of the tilted surface models. It assumes that all of the diffuse radiation is uniformly distributed over the complete sky dome, and is independent of the azimuth and zenith angles. The diffuse radiation per unit area tilted surface is given by the product of the diffuse sky radiation and the view factor from the surface to the sky, which is given as $\frac{(1+\cos\beta)}{2}$.

Combining the three components, on an hourly basis the total radiation on the tilted surface becomes

$$I_T = r_b \, I_b + \frac{1+\cos(\beta)}{2} I_d + \frac{1-\cos(\beta)}{2} \rho \, (I_b + I_d) \tag{3.13}$$

The factors $\frac{1+\cos(\beta)}{2}$ and $\frac{1-\cos(\beta)}{2}$ are known as the view factors of the tilted surface to the sky and to the ground respectively. The model gives a good approximation during completely cloudy skies, but its validity decreases as the sky becomes clearer due to the effects of the circumsolar and horizon brightening anisotropic effects.

The Hay and Davies[41] model take into account both circumsolar and isotropic diffuse radiation by including an anisotropy index, A_I which defines the portion of diffuse radiation to be treated as circumsolar. This then makes the circumsolar diffuse projected onto the tilted surface to be given by

$$I_{T,cir} = I_d A_I R_b \tag{3.14}$$

The remaining, isotropic, diffuse radiation is then given by

$$I_{T,iso} = I_d \left[(1 - A_I)\left(\frac{1+\cos\beta}{2}\right) \right] \tag{3.15}$$

The total diffuse radiation on a tilted surface is then given by

$$I_{d,T} = I_d \left[(1 - A_I)\left(\frac{1+\cos\beta}{2}\right) + A_I R_b \right] \tag{3.16}$$

The Perezl Model[42] takes account of both isotropic, circumsolar and horizon diffuse radiation by using two empirical coefficients based on two years of data. It is widely used in hourly applications, and has been incorporated into photovoltaic simulation program such as PVFORM. It incorporates a geometric description of the sky hemisphere superimposing a circumsolar disc and horizon band on an isotropic background as shown in Figure 3., and an empirical component which establishes the value of the brightness coefficients F_1 and F_2 as a function of insolation conditions. These conditions are parameterised by the solar zenith angle, the horizontal diffuse radiation I_h and the parameter ε given by

$$\varepsilon = \frac{I_b + I_{d,h}}{I_{d,h}}$$

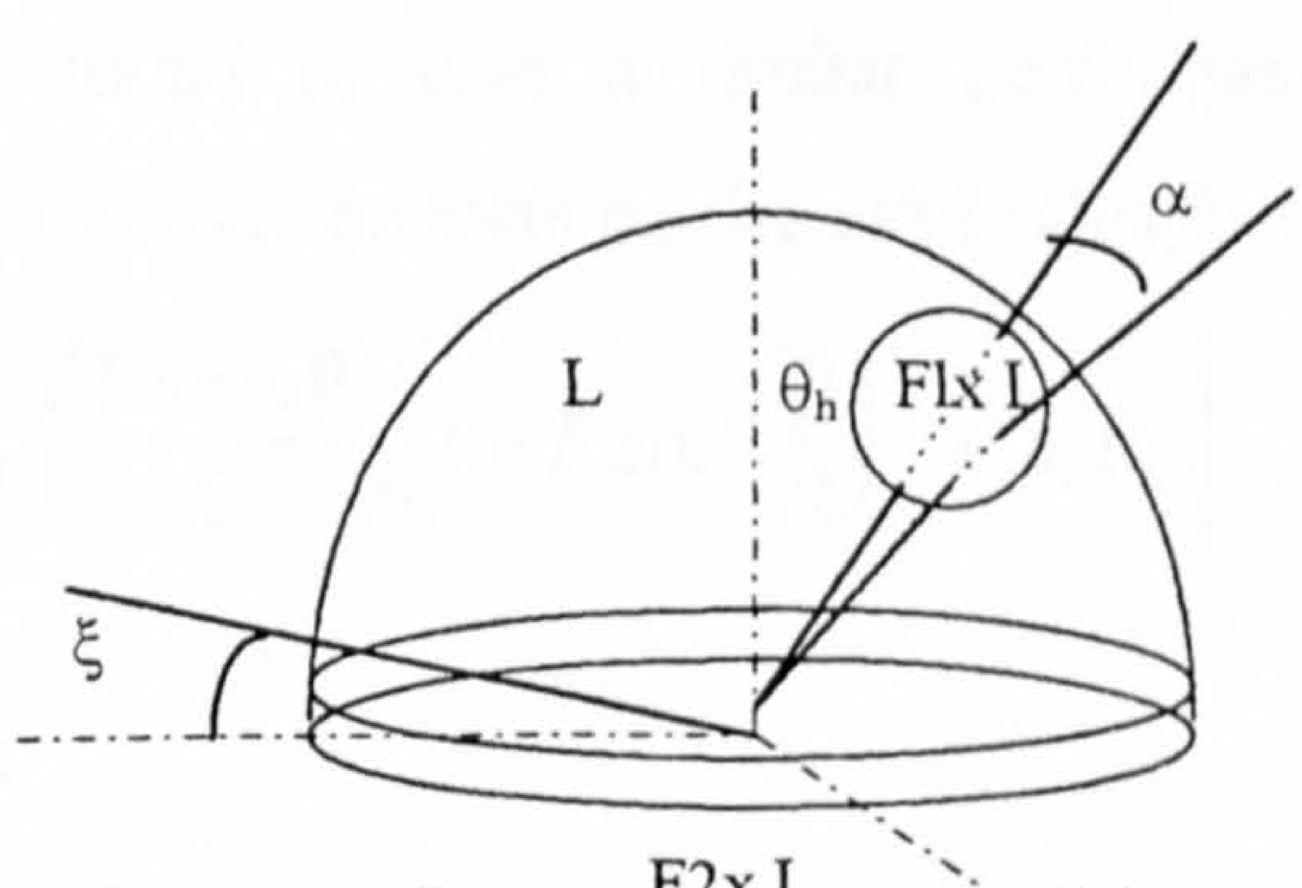


Figure 3.5: Perez model representation of sky hemisphere

Assuming that radiances in the circumsolar and horizon regions are F_1 and F_2 times of the background then the diffuse incident irradiance on a tilted surface is given by

$$I_c = I_h\left[\frac{0.5(1+\cos\beta)+a(F_1-1)+b(F_2-1)}{1+c(F_1-1)+d(F_2-1)}\right] \tag{3.17}$$

where a and b are the solid angles occupied respectively by the circumsolar region and the horizon band weighted by their average incidence on the slope. The parameters c and d are equivalent to a and b but for the horizontal. A three co-ordinate system of $(Z, I_{d,h}, \varepsilon)$ then gives a sky condition categories for each of which a pair of (F_1, F_2) coefficients are established using least square fitting of the equation above to actual recorded data. This was simplified to give the Perez2 model[43], which uses a point source circumsolar region with empirical coefficients and is represented by the equation

$$I_c = I_h\left[0.5(1+\cos\beta)(1-F_1')+F_1'(a/c)+bF_2'\sin\beta\right] \tag{3.18}$$

where $$F_1' = \frac{c(F_1-1)}{1+c(F_1-1)+d(F_2-1)} \quad \text{and} \quad F_2' = \frac{d(F_2-1)}{1+c(F_1-1)+d(F_2-1)} \tag{3.19a,b}$$

The Klucher Model[44] improves the Hay Model by adding a horizon brightening term. The horizon brightening effects were originally approximated by applying a correction factor to the isotropic diffuse radiation given as $\left[1+\sin^3(\beta/2)\right]$ [45]. This accounted for clear sky conditions only. Klucher imposed a modulating factor which forced the anisotropic correction to approach unity under cloudy sky conditions by going to zero, so that the model reduces to the isotropic sky model. The correction factor therefore becomes $\left[1+F\sin^3(\beta/2)\right]$ where $F = 1-(I_d/I)^2$. Alternatively, the factor $F=\sqrt{I_b/I}$, which has been found to give a similar performance for modulating the horizon brightening diffuse correction term can be used. This then gives the anisotropic models as

$$I_{d,T} = I_d\left[(1-A_I)\left(\frac{1+\cos\beta}{2}\right)\left(1+F\sin^3\left(\frac{\beta}{2}\right)\right)+A_I R_b\right] \tag{3.20}$$

3.4 Building Geometrical Area Algorithms

3.4.1 Methods of Computing Insolation of Exposed Building Surfaces

Solar modelling involves predicting insolation and shading patches as a function of solar position and the geometry of obstacles. This requires knowledge of the magnitude and position of the portions exposed to insolation. These quantities are time dependent and are determined separately for each external surface combination windows and wall-surfaces. This data is required to predict the external surface solar absorption, and the absorption, transmission and reflection of the transparent surfaces.

There are two methods of computing the insolation data based on the geometry and solar position. These are the hidden surface method and the point projection technique.

3.4.1a The Hidden Surface Method

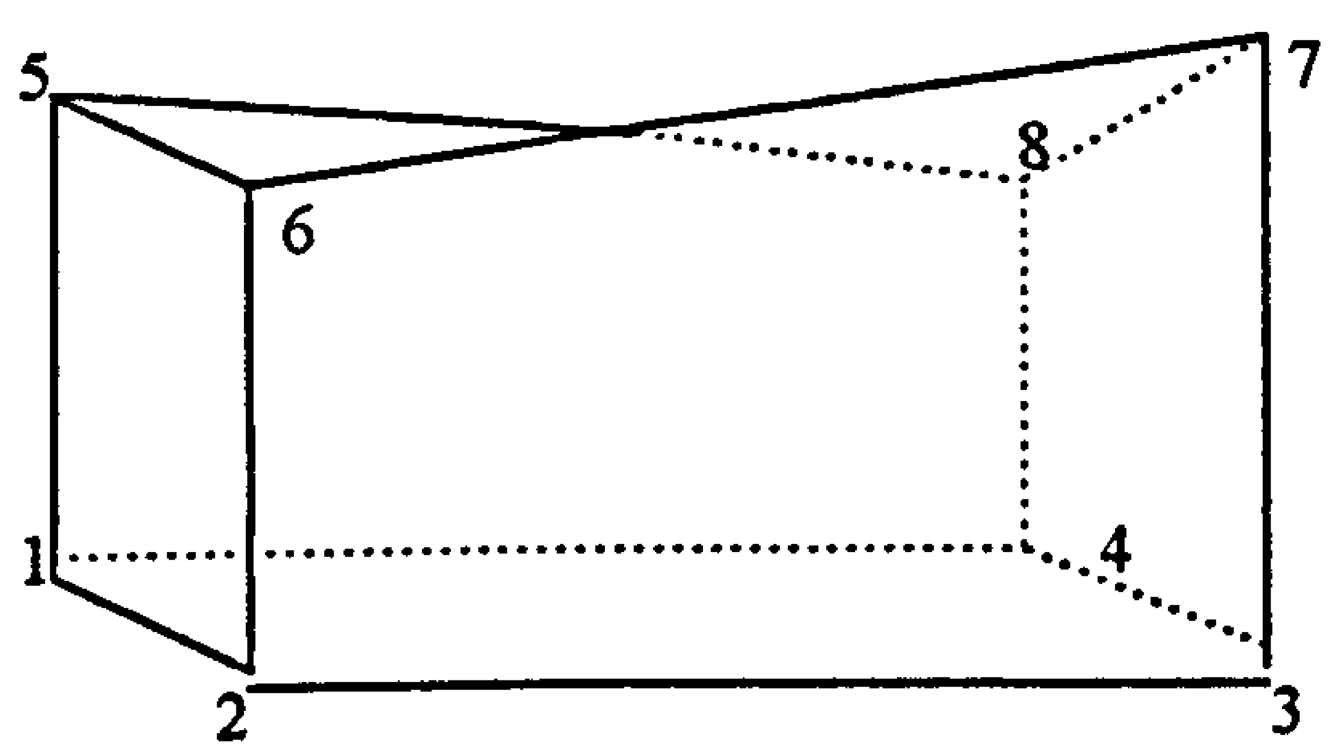
The hidden surface method involves the clipping of surface polygons, one against another, until only those polygon portions remain that will be viewed from some chosen viewpoint, taken as the sun for insolation prediction. Colour and texture can be added [49] to produce realistic images[50]. Characterisations of several hidden surface algorithms have been produced(51).

3.4.1b The Point Projection Technique

The point projection technique is used to quantify the insolation patch and has less potential for visualisation. The target and obstruction objects, are each defined relative to some site Cartesian coordinate system. The XZ plane of the coordinate system is then relocated in the plane of each face of the target body in turn. Each obstruction object is then projected, parallel to the sun's rays, onto the face and the projected image expressed relative to the local face coordinate system. A simple grid can then be superimposed on each opaque and transparent surface allowing grid point containment testing against each individual shadow polygon. Prediction accuracy is controlled by adjusting the number of grid subdivisions of the homogenous face.

3.4.2 General Building Topology

Many geometrical operations exist[52]. A building can be considered to be a generally shaped volume bounded by walls which constitute planar polygons. The coordinates of the vertices of the walls are specified with respect to an arbitrarily chosen Cartesian co-ordinate system. The topology of the building is then given by a list of ordered vertex descriptions of each bounding wall. A convention of specifying the vertices anticlockwise when each polygon is viewed from the outside can be used. Windows can be considered as holes in the polygons and then specified by reversing the vertex order with respect to the building. This allows single and composite transformations to perform basic operations to be applied. These operations produce modified vertex coordinates, but without corresponding topological modification Therefore, the topology need to be held only once for any geometry, because of its independence from scale and orientation. The applicability of this procedure to energy modelling removes the need for more advanced techniques of surface representation[53].



Wall	Ordered Description
1	1,2,3,4
2	2,3,7,6
3	3,4,8,7
4	4,1,5,8
5	8,5,6,7
6	1,4,3,2

Figure 3.8 Ordered Vertex Description

For any wall(planar polygon), denoted by p, where NV is the number of vertices in the polgon and x,y,z are the corresponding coordinates, the following summations are applied to the polygon vertices

$$\left.\begin{aligned} xsum_p &= \sum_{i=1}^{NV}\left(y_i z_j + z_i y_j\right) \\ ysum_p &= \sum_{i=1}^{NV}\left(z_i x_j + x_i z_j\right) \\ zsum_p &= \sum_{i=1}^{NV}\left(x_i y_j + y_i x_j\right) \end{aligned}\right\} \begin{aligned} &j = i+1 \\ &for\ j > NV; \quad j = 1 \end{aligned} \qquad (3.24)$$

The area of this polygon is then given by

$$Area_p = 0.5\left(xsum_p^2 + ysum_p^2 + xsum_p^2\right)^{0.5} \qquad (3.25)$$

and the perimeter is given by

$$Perim_p = \sum_{i=1}^{NV}\left[\left(x_j - x_i\right)^2 + \left(y_j - y_i\right)^2 + \left(z_j - z_i\right)^2\right]^{0.5} \qquad (3.26)$$

$$for\ j > NV; \quad j = 1$$

The orientation of the wall is defined by the azimuth angle α_p and the elevation angle β_p. The azimuth is the angle between the Y axis(usually north pointing) and the projection of the polygon outward facing normal onto the XY plane(usually the horizontal plane). The plane elevation is the angle between the outward facing normal and the projection of this normal onto a plane parallel to the XY plane. The angles are shown in Figure 3.7. Thus, the azimuth is given by

$$\alpha_p = \tan^{-1}\left(\frac{xsum_p}{ysum_p}\right) \qquad (3.27)$$

$$where \quad for\ ysum_p = 0 \quad \begin{aligned} \alpha_p &= -90° \ \ for \ \ xsum_p < 0 \\ \alpha_p &= \ \ \ 0° \ \ for \ \ xsum_p = 0 \\ \alpha_p &= \ \ 90° \ \ for \ \ xsum_p > 0 \end{aligned}$$

and for the elevation

$$\beta_p = \tan^{-1}\left[\frac{zsum_p}{\left(xsum_p^2 + ysum_p^2\right)^{0.5}}\right] \qquad (3.28)$$

$$where \quad for\, xsum_p^2 + ysum_p^2 = 0 \quad \beta_p = -90° \quad for \quad z\,sum_p < 0$$
$$\beta_p = 0° \quad for \quad z\,sum_p = 0$$
$$\beta_p = 90° \quad for \quad z\,sum_p > 0$$

Algebraic summation of the volumes of the prism formed by connecting the vertices of each polygon in turn to some arbitrary point gives the contained volume.. The vertex ordering of polygons specified as holes must be reversed.. Thus the volume is given by:

$$vol = \frac{1}{6}\sum_{j=1}^{NP}\left[\left(x_{j1}xsum_j\right) + \left(y_{j1}ysum_j\right) + \left(z_{j1}zsum_j\right)\right] \tag{3.29}$$

where x_{j1}, y_{j1} and z_{j1} are the coordinates of the first vertex in polygon j, and NP is the total number of polygons.

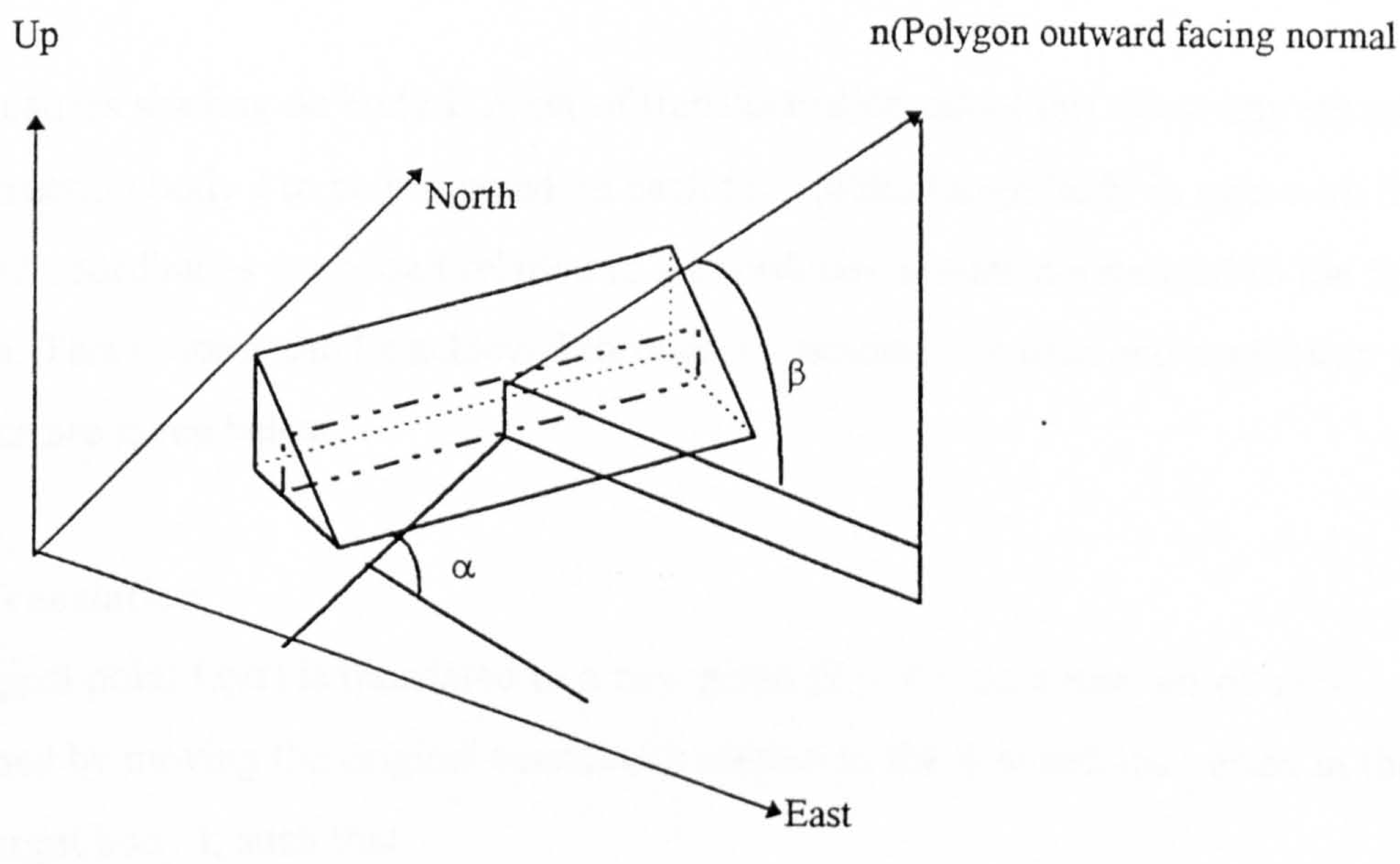


Figure 3.9: Azimuth and Elevation Angles

3.4.3 Insolation Transformation Equations

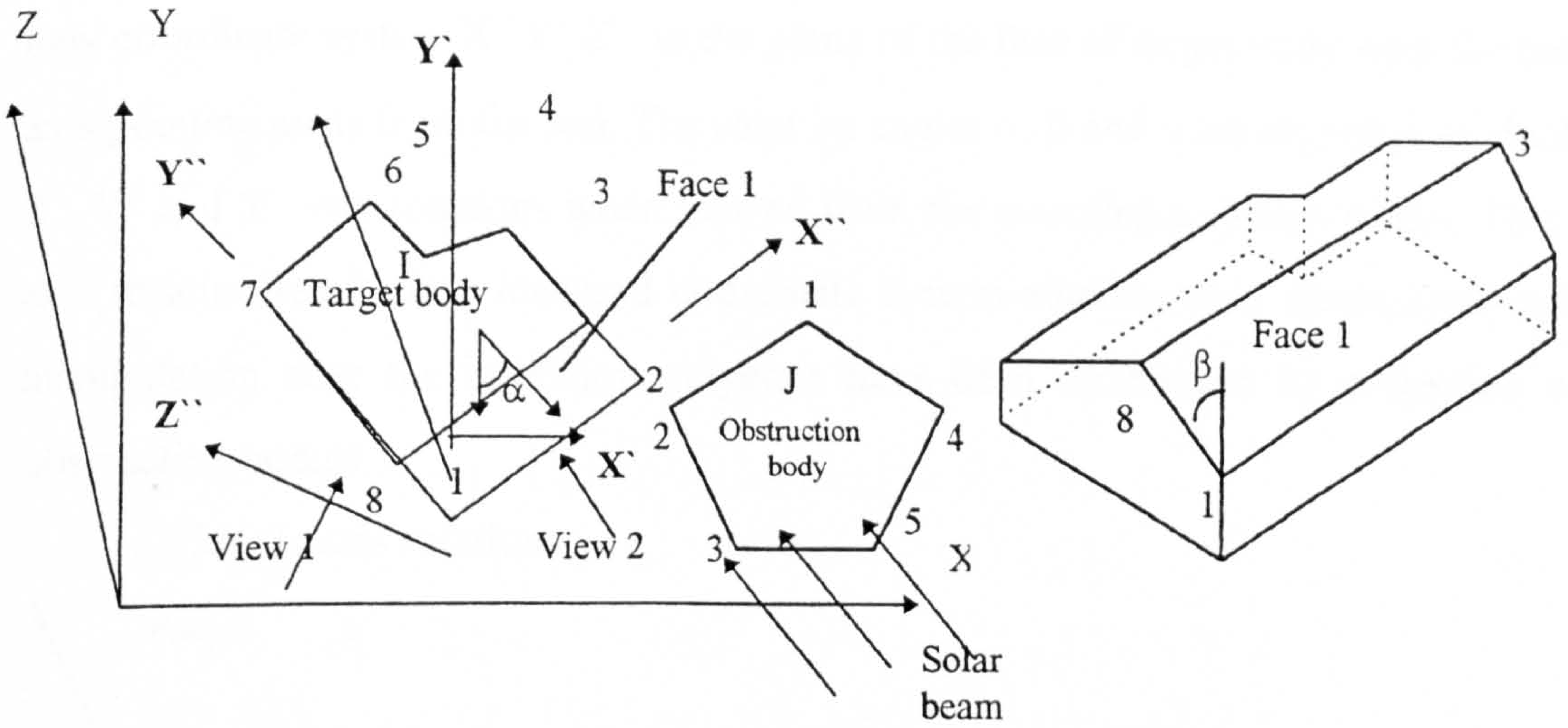


Figure 3.10: Obstructed and Obstructing Bodies in a Right Hand Co-ordinate System[54]

Body J causes shading on body I. A set of transformation equations allow any vertex of the obstruction body J to be projected on each face of the target body in turn with the projected coordinates expressed relative to a coordinate system normalised to the face in question. This process can be achieved through translation, rotation and projection whose equations are given below:

3.4.3aTranslation

An original point (xyz) is translated to a new point (x\`y\`z\`) on a new set of axes established by moving the original coordinate system to the first defined vertex in the face of the target body I; such that

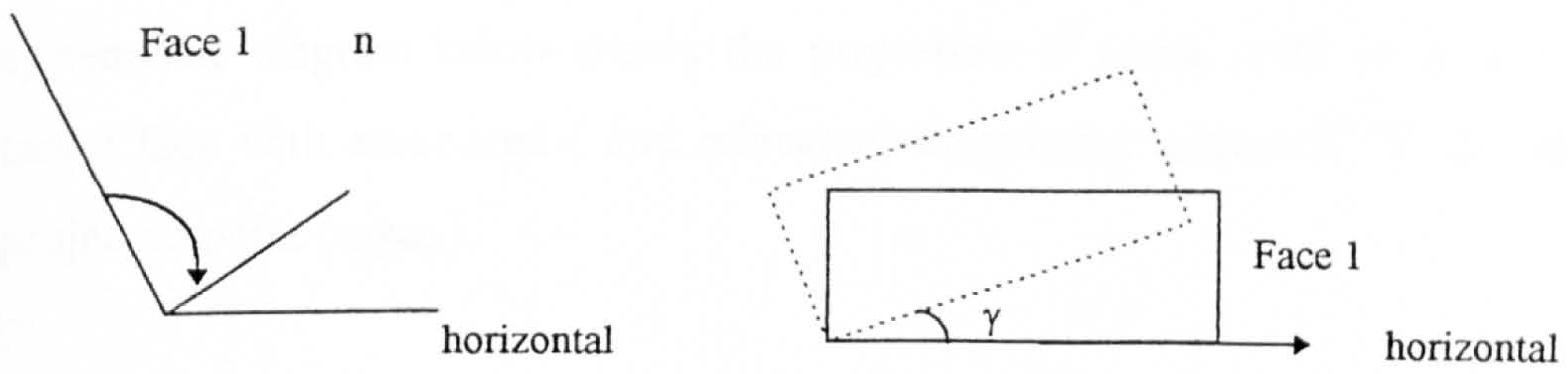
$$\left(x^{`}y^{`}z^{`}\right)=\left(x \quad y \quad z \quad 1\right)\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ -x_0 & -y_0 & -z_0 \end{bmatrix} \tag{3.30}$$

where (x_0 y_0 z_0) is the new origin in old coordinates, i.e. components of translation in the X, Y and Z directions.

3.4.3b Rotation

The translated axes X``, Y`` and Z`` is aligned, by rotation, to the X``Z`` plane of the new coordinate system X``Y``Z`` in the plane of the face of target body with the new Y`` axis pointing away from the sun. The rotation angles α, β and γ are regarded as clockwise Z`, Y` and Y` axis rotations when viewed from the coordinate system origin. This three axis rotation results in a localised coordinate system allowing two dimensional polygon manipulation after the insolation polygons have been established by projection of the obstruction bodies.

View 1: axis rotation



View 2: Z axis rotation

Figure 3.11

Any point (x`y`z`) therefore transforms to the point (x``y``z``) according to the relationship:

$$(x``y``z``) = (x'y'z')\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & \sin\beta \\ 0 & -\sin\beta & \cos\beta \end{bmatrix}\begin{bmatrix} \cos\gamma & 0 & \sin\gamma \\ 0 & 1 & 0 \\ -\sin\gamma & 0 & \cos\gamma \end{bmatrix}\begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The final axes transformation is then

$$(x``y``z``) = (xyz1)\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ -x0 & -y0 & -z0 \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & \sin\beta \\ 0 & -\sin\beta & \cos\beta \end{bmatrix}\begin{bmatrix} \cos\gamma & 0 & \sin\gamma \\ 0 & 1 & 0 \\ -\sin\gamma & 0 & \cos\gamma \end{bmatrix}$$

$$\times\begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (3.31)$$

The Z` axis rotation α is related to the face azimuth, a_f by

$\alpha = a_f - 180 \qquad 0 < a_f \leq 180$

$\alpha = a_f \qquad 180 < a_f \leq 360$

The X` axis rotation β is related to the face elevation, e_f by

$$\beta = e_f \qquad -90 \le e_f \le 90$$

and the Y axis rotation γ is related to the angle, t_f between the line joining the first two vertices of the face with the horizontal by

$$\gamma = -t_f \qquad 0 \le t_f < 360$$

3.4.3c Projection

The vertices of the obstruction object can then be projected onto the X``Z`` plane to give the vertices of the projected shadow polygons relative to the local face coordinate system.The diagram below shows the projection of some point (x``y``z``) onto some target face with associated ( and relocated) coordinate system X``Y``Z`` to give some projected point ($x_p y_p z_p$).

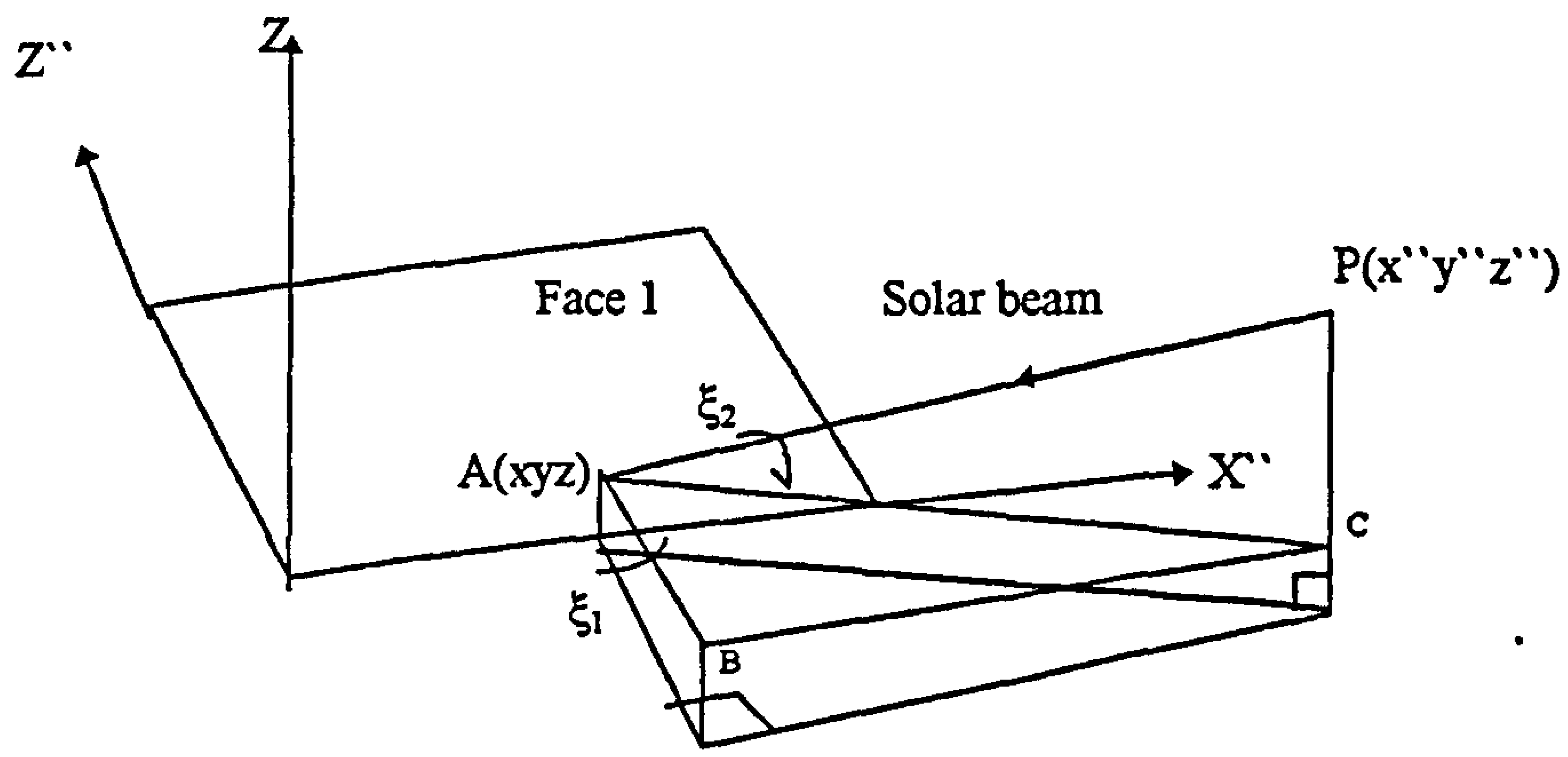


Figure 3.12 Projection of Point (x``y``z``)

$$\tan \xi_1 = \frac{BC}{AB} = \left(x`` - x_p\right) / y'' \qquad \text{for } \xi_1 \text{ positive}$$

$$\tan \xi_1 = \left(x_p - x``\right) / y'' \qquad \text{for } \xi_1 \text{ negative}$$

$$\Rightarrow x_p = x'' \pm y'' \frac{\sin \xi_1}{\cos \xi_1}$$

also

$$\cos \xi_1 = \frac{AB}{AC} = \frac{y``}{AC}$$

$$\Rightarrow AC = \frac{y``}{\cos \xi_1}$$

and

$$\tan\xi_2 = \frac{PC}{AC}$$

$$= \frac{(z'' - z_p)}{AC} \qquad \textit{for } \xi_2 \textit{ positive}$$

$$= \frac{(z_p - z'')}{AC} \qquad \textit{for } \xi_2 \textit{ negative}$$

$$\Rightarrow z_p = z'' \pm AC \tan\xi_2$$

Therefore

$$z_p = z'' \pm y'' \frac{\tan\xi_2}{\cos\xi_1} \quad \textit{and} \quad y_p = 0$$

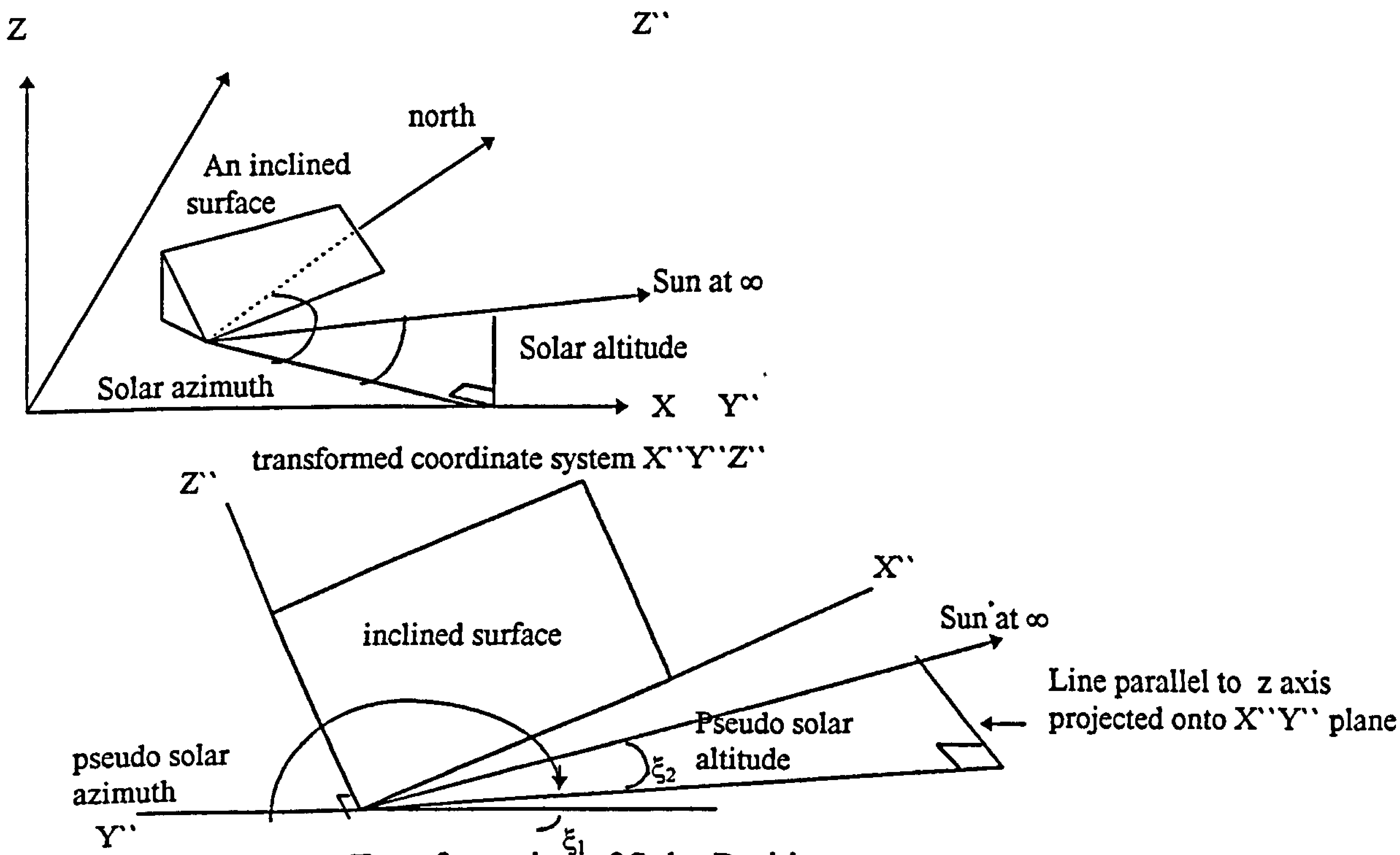


Figure 3.13: Transformation of Solar Position

If y'' ≥ 0 then P lies behind the face relative to the sun and is therefore omitted from processing. This affects the algorithm for bodies partially behind and partially in front of the face in question. The projection is given by

$$(x_p y_p z_p) = (x'' y'' p'') \begin{bmatrix} 1 & 0 & 0 \\ \pm\dfrac{\sin\xi_1}{\cos\xi_1} & 1 & \pm\dfrac{\tan\xi_2}{\cos\xi_1} \\ 0 & 0 & 1 \end{bmatrix} \qquad (3.32)$$

3.4.4 Combined Operations

The complete translation, rotation and projection equation is then given by

$$(x_p y_p z_p) = (xyz1)\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ -x0 & -y0 & -z0 \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & \sin\beta \\ 0 & -\sin\beta & \cos\beta \end{bmatrix}\begin{bmatrix} \cos\gamma & 0 & \sin\gamma \\ 0 & 1 & 0 \\ -\sin\gamma & 0 & \cos\gamma \end{bmatrix}$$

$$\times\begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 \\ \pm\dfrac{\sin\xi_1}{\cos\xi_1} & 1 & \pm\dfrac{\tan\xi_2}{\cos\xi_1} \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \left[(x-x_0),(y-y_0)\cos\beta+(z-z_0)\sin\beta,-(y-y_0)\sin\beta+(z-z_0)\cos\beta\right]$$

$$\times\begin{bmatrix} \cos\gamma & 0 & \sin\gamma \\ 0 & 1 & 0 \\ -\sin\gamma & 0 & \cos\gamma \end{bmatrix}\begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 \\ \pm\dfrac{\sin\xi_1}{\cos\xi_1} & 1 & \pm\dfrac{\tan\xi_2}{\cos\xi_1} \\ 0 & 0 & 1 \end{bmatrix}$$

$$= (x_T\cos\gamma\cos\alpha + y_T\sin\beta\sin\gamma\cos\alpha - z_T\cos\beta\sin\gamma\cos\alpha - y_T\cos\beta\sin\alpha$$
$$+ z_T\sin\beta\sin\alpha, \quad -x_T\cos\gamma\sin\alpha - y_T\sin\beta\sin\gamma\sin\alpha + z_T\cos\beta\sin\gamma\sin\alpha$$
$$+ y_T\cos\beta\cos\alpha + z_T\sin\beta\cos\alpha, \quad x_T\sin\gamma - y_T\sin\beta\cos\gamma + z_T\cos\beta\cos\gamma)$$

$$\times\begin{bmatrix} 1 & 0 & 0 \\ \pm\dfrac{\sin\xi_1}{\cos\xi_1} & 1 & \pm\dfrac{\tan\xi_2}{\cos\xi_1} \\ 0 & 0 & 1 \end{bmatrix} \qquad (3.33)$$

where $x_t = x\text{-}x_0\ y_t = y\text{-}y_0,\ z_t = z\text{-}z_0$. Therefore

$$x_P = (x_T\cos\gamma\cos\alpha + y_T\sin\beta\sin\gamma\cos\alpha - z_T\cos\beta\sin\gamma\cos\alpha + y_T\cos\beta\sin\alpha$$
$$+ z_T\sin\beta\sin\alpha - x_T\cos\gamma\sin\alpha(\pm\tan\xi_1) - y_T\sin\beta\sin\gamma\sin\alpha(\pm\tan\xi_1)$$
$$+ z_T\cos\beta\sin\gamma\sin\alpha(\pm\tan\xi_1) + y_T\cos\beta\cos\alpha(\pm\tan\xi_1) + z_T\sin\beta\cos\alpha(\pm\tan\xi_1))$$

$$y_P = (-x_T\cos\gamma\sin\alpha - y_T\sin\beta\sin\gamma\sin\alpha + z_T\cos\beta\sin\gamma\sin\alpha$$
$$+ y_T\cos\beta\cos\alpha + z_T\sin\beta\cos\alpha)$$

$$z_p = -x_T\cos\gamma\sin\alpha\left(\pm\frac{\tan\xi_2}{\cos\xi_1}\right) - y_T\sin\beta\sin\gamma\sin\alpha\left(\pm\frac{\tan\xi_2}{\cos\xi_1}\right)$$
$$z_T\sin\beta\cos\alpha\left(\pm\frac{\tan\xi_2}{\cos\xi_1}\right) + x_T\sin\gamma - y_T + z_T\cos\beta\sin\gamma\sin\alpha\left(\pm\frac{\tan\xi_2}{\cos\xi_1}\right)$$
$$+ y_T\cos\beta\cos\alpha\left(\pm\frac{\tan\xi_2}{\cos\xi_1}\right) + \sin\beta\cos\gamma + z_T\cos\beta\cos\gamma$$

(3.34a,b,c)

3.4.5 Line/Surface Intersection

The plane equation is given by

$$Ax + By + Cz + D = 0$$

where the plane coefficients A, B, C and D are determined from the knowledge of 3 non collinear points lying on the plane. The general plane equation and form a set of homogenous equations with the 3 equations for each point represented by

$$Ax_i + By_i + Cz_i + D = 0 \qquad (3.35)$$

where i=1,2,3. The determinant of this set of equations must be zero if it has a solution. Therefore

$$\begin{vmatrix} x & y & z & 1 \\ x_1 & y_1 & z_1 & 1 \\ x_2 & y_2 & z_2 & 1 \\ x_3 & y_3 & z_3 & 1 \end{vmatrix} = 0 \qquad (3.36)$$

giving

$$A = \begin{vmatrix} y_1 & z_1 & 1 \\ y_2 & z_2 & 1 \\ y_3 & z_3 & 1 \end{vmatrix}, \quad B = -\begin{vmatrix} x_1 & z_1 & 1 \\ x_2 & z_2 & 1 \\ x_3 & z_3 & 1 \end{vmatrix}, \quad C = \begin{vmatrix} x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \\ x_3 & y_3 & 1 \end{vmatrix}, \quad D = -\begin{vmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{vmatrix}$$

A line intersecting with a plane at point p is shown in Figure 3.14

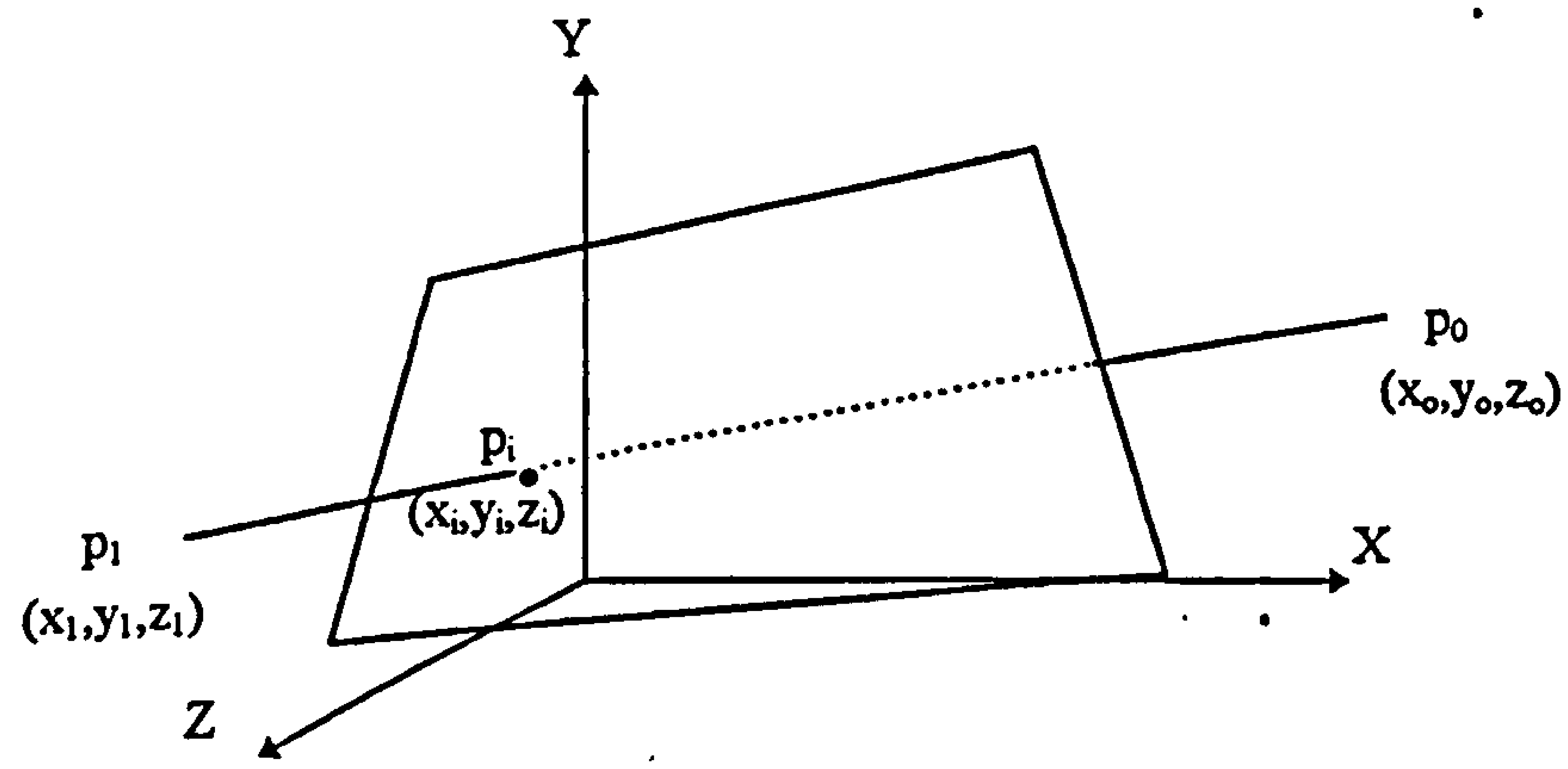


Figure 3.14: Line/surface intersection

The coordinates of p, (x_i, y_i,z_i) are found by equating the line equation to the plane equation.

$$Ax_i + By_i + Cz_i + D = 0,$$

$$x_i = (x_1 - x_0)u_i + x_0, \qquad y_i = (y_1 - y_0)u_i + y_0, \qquad z_i = (z_1 - z_0)u_i + z_0$$

u_i is then given as

$$u_i = \frac{Ax_i + By_i + Cz_i + D}{A(x_i - x_0) + B(y_i - y_0) + C(z_i - z_0)} \tag{3.37}$$

If $0<u_i<1$, then there is intersection and the equations can be solved for the coordinates of p.

3.5 Software Development of Resource Estimation Tool

3.5.1 Construction of Database

The algorithmic development implies that analysis of a building or a cityscape involves the construction of a database containing numerical representations of the geometry of the buildings and a weather database. The building geometry database can be constructed manually by entering individual coordinates of each vertex of the polyhedron representation of the building. Alternatively, it can be constructed from formatted files generated by computer aided design software such as AutoCAD which produce .DXF files. These files then contain cityscapes in the form of sequences of building data comprising of 3 dimensional coordinates of roof and ground coordinates.

The building vertices are generated from the photogrammetric digitisation of stereographic images of the chosen cityscape. The digitised roof and ground vertices are associated with separate drawing layers within AutoCAD. Conventionally, photogrammetric input involves establishing ground topology using a proprietary third-party mapping program which allows a series of ground coordinates to be entered and then forms the ground topology through triangulation between specified coordinates. The triangular ground surfaces are then stored within the same file as the building data. The ground topology is then established as a series of interlocking triangles, after which the roof vertices are digitised in an anticlockwise sequential order. An AUTOLISP routine is then invoked from within AutoCAD and this allows the roof vertices to be projected vertically downwards to the lowest point of the ground topology. The intersection of these vertical projections with the constituent triangular ground surfaces are then calculated and stored in the building layer in the same order as the roof vertices. Each building within the .DXF file is then processed by a software search for the roof layer code, the entities follow flag, the primary x coordinate flag and then the each roof vertex is read in sequence. The process is repeated for the ground vertices and is continued until the end of file is found.

For a cityscape with m buildings each with n walls, the number of vertices on each building is 2n and the format of the formatted (.OVD) file is as follows

- number of buildings, m.
- number of vertices on building 1, $2n_1$
- x,yz coordinates of vertex 1

  .

  .

- x,y,z coordinates of vertex $2n_1$

  .

  .

- number of vertices on building m, $2n_m$
- x,yz coordinates of vertex 1
- .
- .
- x,y,z coordinates of vertex $2n_m$

The database of the buildings is as follows

Non-Air-Conditioned Government Commercial Office Building
1
8
1475.000 1553.835 1125.000
1561.132 1553.835 1125.000
1561.132 1553.835 1145.750
1475.000 1553.835 1145.750
1475.000 1487.200 1125.000
1561.132 1487.200 1125.000
1561.132 1487.200 1145.750
1475.000 1487.200 1145.750
6
4 1 2 6 5
4 2 3 7 6
4 3 4 8 7
4 4 1 5 8

Tenant Occupied Commercial Building
1
16
1475.000000 1535.730000 1125.000000
1475.000000 1535.730000 1135.500000
1476.750000 1535.730000 1135.500000
1476.750000 1535.730000 1139.500000
1475.000000 1535.730000 1139.500000
1475.000000 1535.730000 1149.700000
1493.700000 1535.730000 1149.700000
1493.700000 1535.730000 1148.100000
1496.300000 1535.730000 1148.100000
1496.300000 1535.730000 1149.700000
1504.800000 1535.730000 1149.700000
1504.800000 1535.730000 1125.000000
1496.200000 1535.730000 1125.000000
1496.200000 1535.730000 1126.500000
1493.700000 1535.730000 1126.500000
1493.700000 1535.730000 1125.000000
1475.000000 1474.000000 1125.000000
1475.000000 1474.000000 1135.500000
1476.750000 1474.000000 1135.500000
1476.750000 1474.000000 1139.500000
1475.000000 1474.000000 1139.500000
1475.000000 1474.000000 1149.700000
1493.700000 1474.000000 1149.700000
1493.700000 1474.000000 1148.100000
1496.300000 1474.000000 1148.100000
1496.300000 1474.000000 1149.700000
1504.800000 1474.000000 1149.700000
1504.800000 1474.000000 1125.000000
1496.200000 1474.000000 1125.000000
1496.200000 1474.000000 1126.500000
1493.700000 1474.000000 1126.500000
1493.700000 1474.000000 1125.000000
18
4 1 2 18 17
4 2 3 19 18
4 3 4 20 19
4 4 5 21 20
4 5 6 22 21
4 6 7 23 22
4 7 8 24 23
4 8 9 25 24
4 9 10 26 25
4 10 11 27 26
4 11 12 28 27
4 12 13 29 28
4 13 14 30 29
4 14 15 31 30
4 15 16 32 31
4 16 17 1 32
16 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32

Prestige Modern Building
1
16
987.500000 1559.670000 844.696000
987.500000 1559.670000 854.871000
994.696000 1559.670000 862.067000
1004.87100 1559.670000 862.567000
1012.06700 1559.670000 854.871000
1012.06700 1559.670000 844.696000
1004.87100 1559.670000 837.500000
994.696000 1559.670000 837.500000
987.500000 1475.200000 844.696000
987.500000 1475.200000 854.871000
994.696000 1475.200000 862.067000
1004.87100 1475.200000 862.567000
1012.06700 1475.200000 854.871000
1012.06700 1475.200000 844.696000
1004.87100 1475.200000 837.500000
994.696000 1475.200000 837.500000
10
4 1 2 10 9
4 2 3 11 10
4 3 4 12 11
4 4 5 13 14
4 5 6 14 15
4 6 7 15 16
4 7 8 16 1
8 1 2 3 4 5 6 7 8
8 9 10 11 12 13 14 15 16

The Passively Ventilated Building
1
8
1337.500 1504.900 175.000
1335.273 1504.900 190.844
1473.911 1504.900 210.329
1476.136 1504.900 194.484
1337.500 1470.600 175.000
1335.273 1470.600 190.844
1473.911 1470.600 210.329
1476.136 1470.600 194.484
6
4 1 2 6 5
4 2 3 7 6
4 3 4 8 7
4 4 1 5 8
4 1 2 3 4
4 5 6 7 8

Business Hotel
The database for Business Hotel has been omitted because its curved shaped was represented by 12 sections which gave rise to 56 vertices.

The weather database consists of a 1994 weather file created from hourly weather data obtained from the meteorological station in the benchmark city.

3.5.2 Activities of The Software Tool

A software tool is then required to fulfil the following functions:

- Communicate with the user
- Extracting the geometry of a given building or set of buildings from the database vertex sequences and establishing a formatted file for further analysis.
- Producing a visual 3-dimensional representation of the building geometry or cityscape, so that errors in the photogrammetric digitisation or manual input are identified.
- Extract weather data from the weather database for a given location .
- Calculating time-dependent solar angles for each hour of the day over a specified period.
- Calculating the area of the building surfaces
- Calculating solar intensities on arbitrarily orientated surfaces using direct and diffuse solar intensities on horizontal surfaces utilising the available estimation models.
- Calculating the shading effect of other building surfaces.
- Presenting results of shading and insolation over a period of time graphically and in tabular form.

3.5.2 Formulating of The Software Tool

The software achieved this by carrying out preliminary activities such as

- Reading the project (.DAT) file which contains the name of the building, its location, the period of analysis and the name of weather file;
- Reading the .DXF files and converting them to .OVD files;
- Allowing the user to request a visual representation of the building and then showing a wire frame representation of the building on the screen so that the user can visually verify the accuracy of the input building data before prompting the program to begin calculations;
- Reading binary shading factors (.SHD) files and converting their data to form ASCII format (.ASH) files;
- Reading the weather(.ASC) file defined in the building header file;

- Carrying out area calculations, polygon containment tests and insolation calculations for the period defined in the project file
- Creating the results files (.SUM for summary and .HRY for hourly results) for storage of results of calculations;
- Receiving instructions on which results to display from the user and displaying them;

These activities can be represented by the context diagram in Figure 3.15

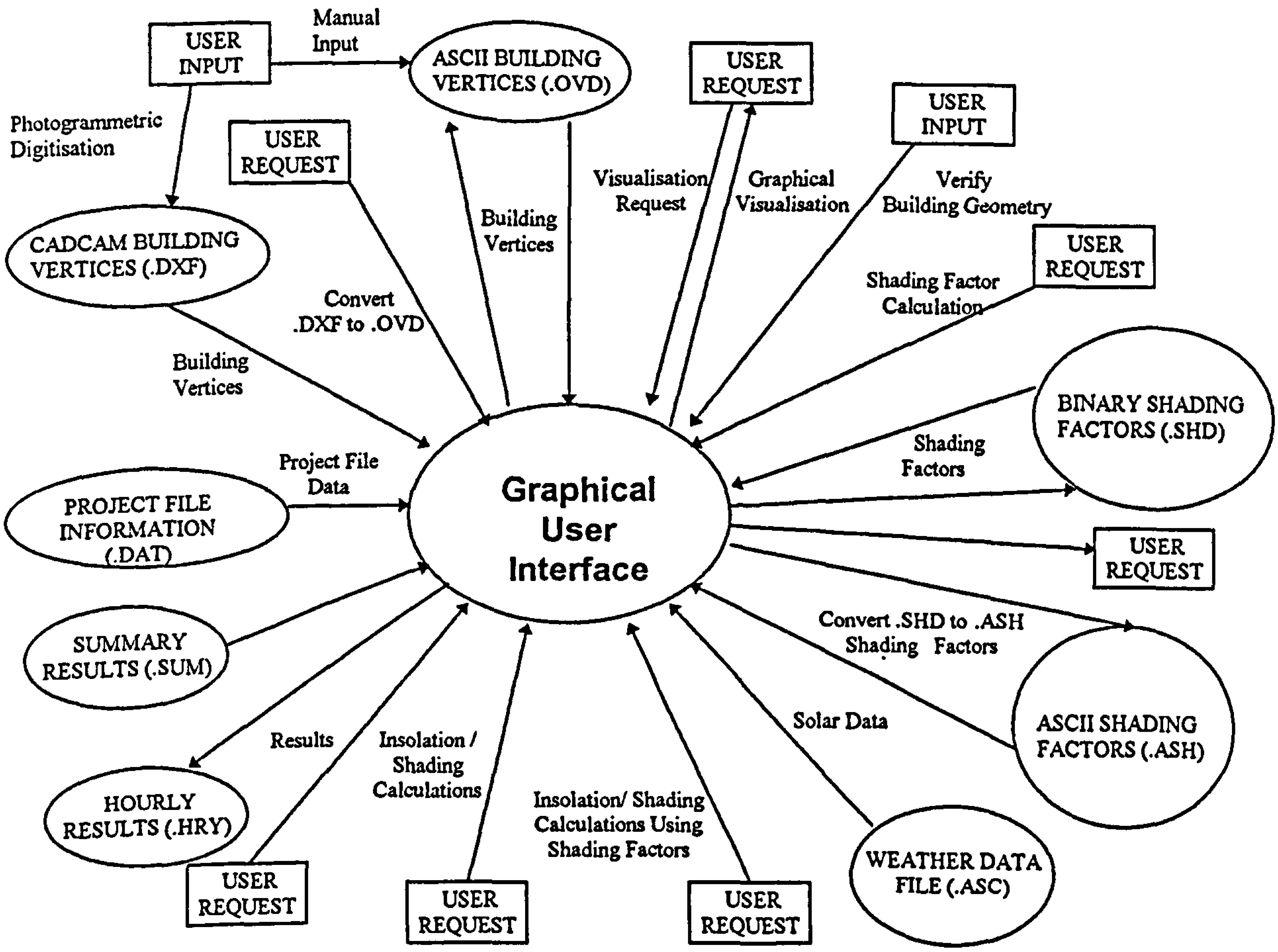


Figure 3.15: Program Context Diagram

3.5.3 Implementing The Software Tool

The project software suite was implemented using the console application of Microsoft Visual C++ 4 software development code so that it could easily adapt to the requirements of the personal computer user and that it could communicate with Microsoft based databases. It consisted of linked object modules each made of a C++ program and consisting of several functions. The list of linked object modules follows.

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Its actions are illustrated in the structured chart in Figure 3.16

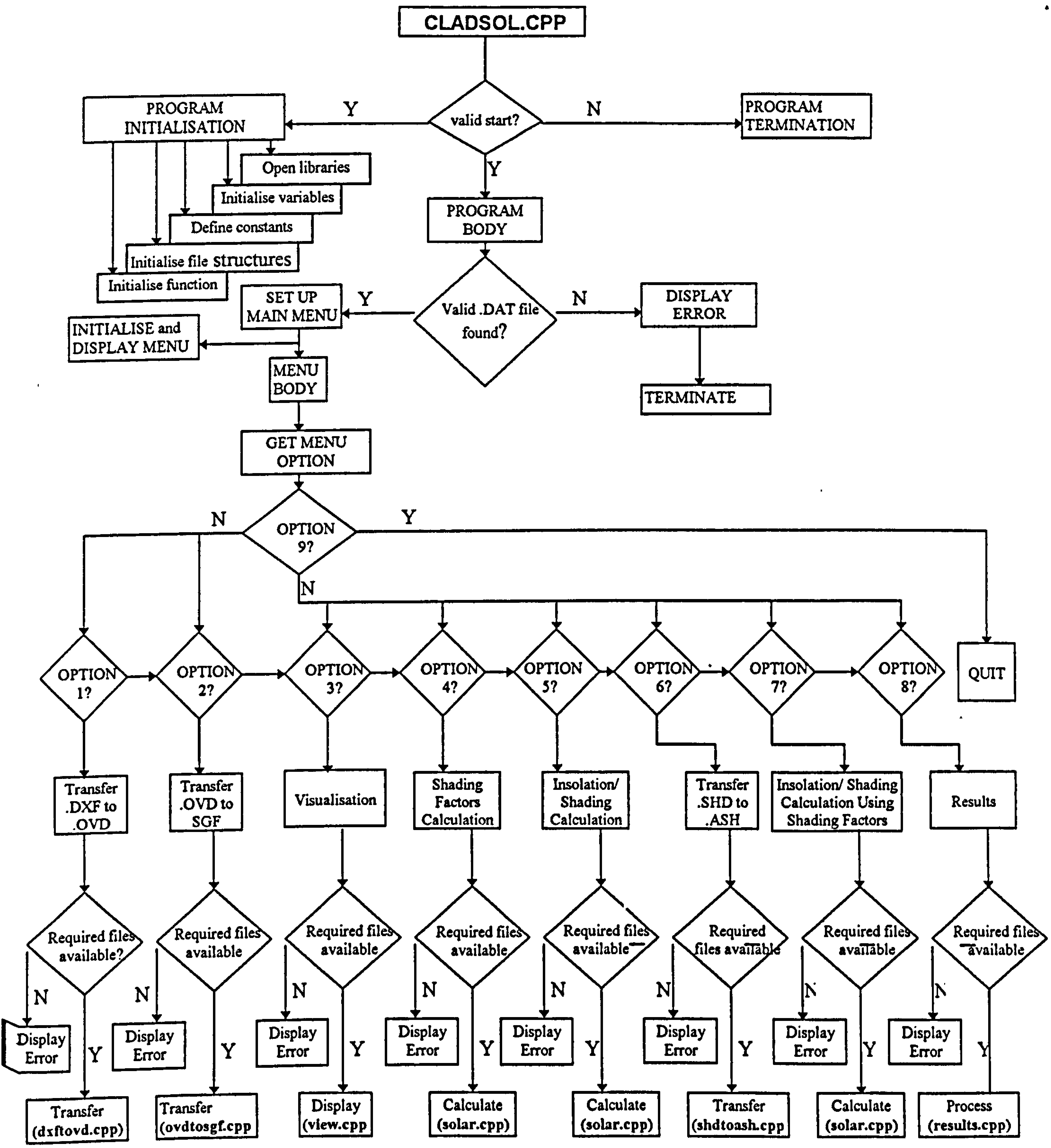

Figure 3.16: Structured Chart of Cladsol.cpp

3.5.3b DXFTOVD.CPP

This module extracts the building geometry data from the data(.DXF) file obtained by photogrammetric digitisation, and converts it to the formatted (.OVD) required for by other program modules.

The structured chart follows.

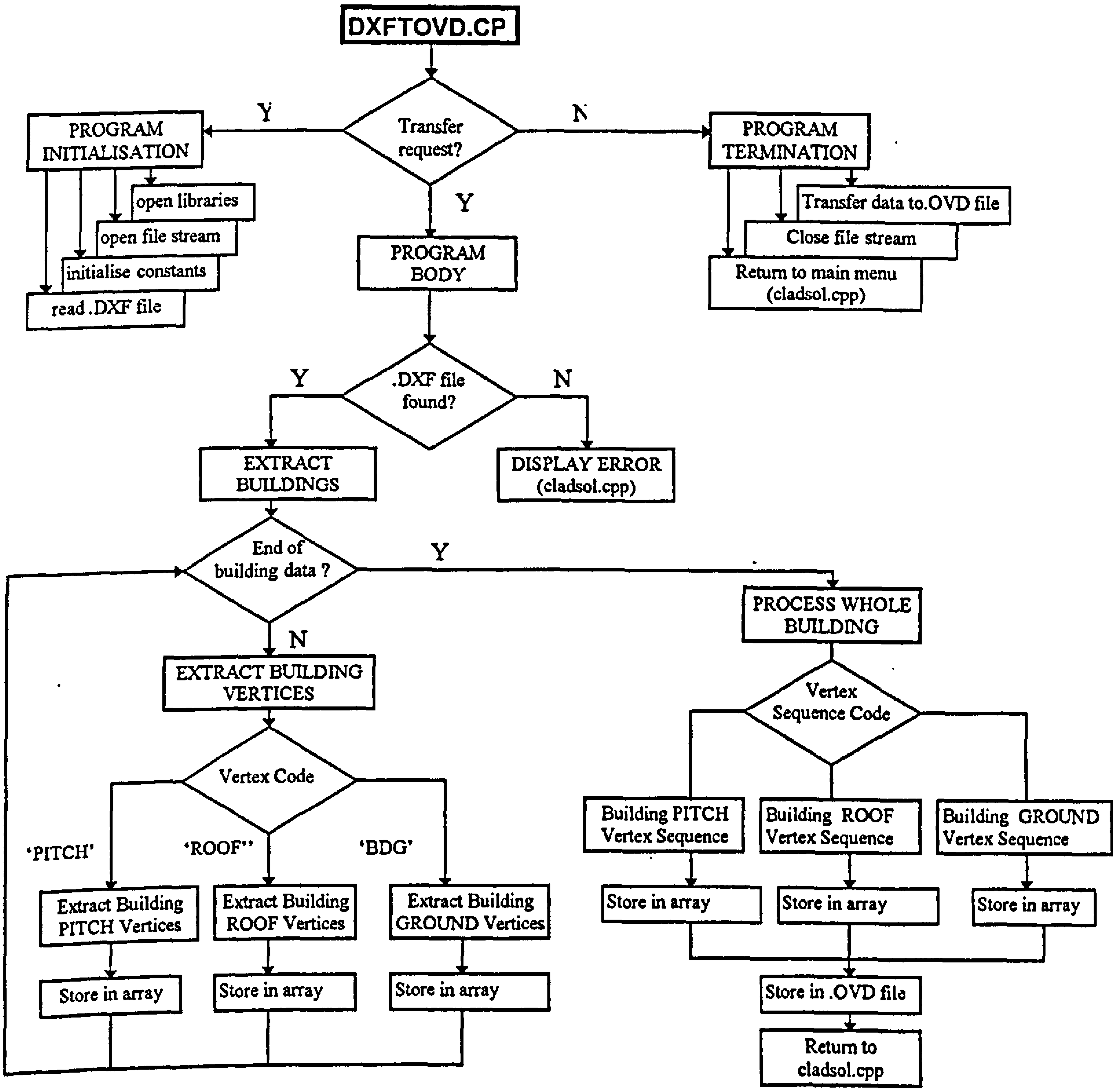

Figure 3.17 Structured Chart of DXFTOVD.CPP

3.5.3c OVDTOSGF.CPP

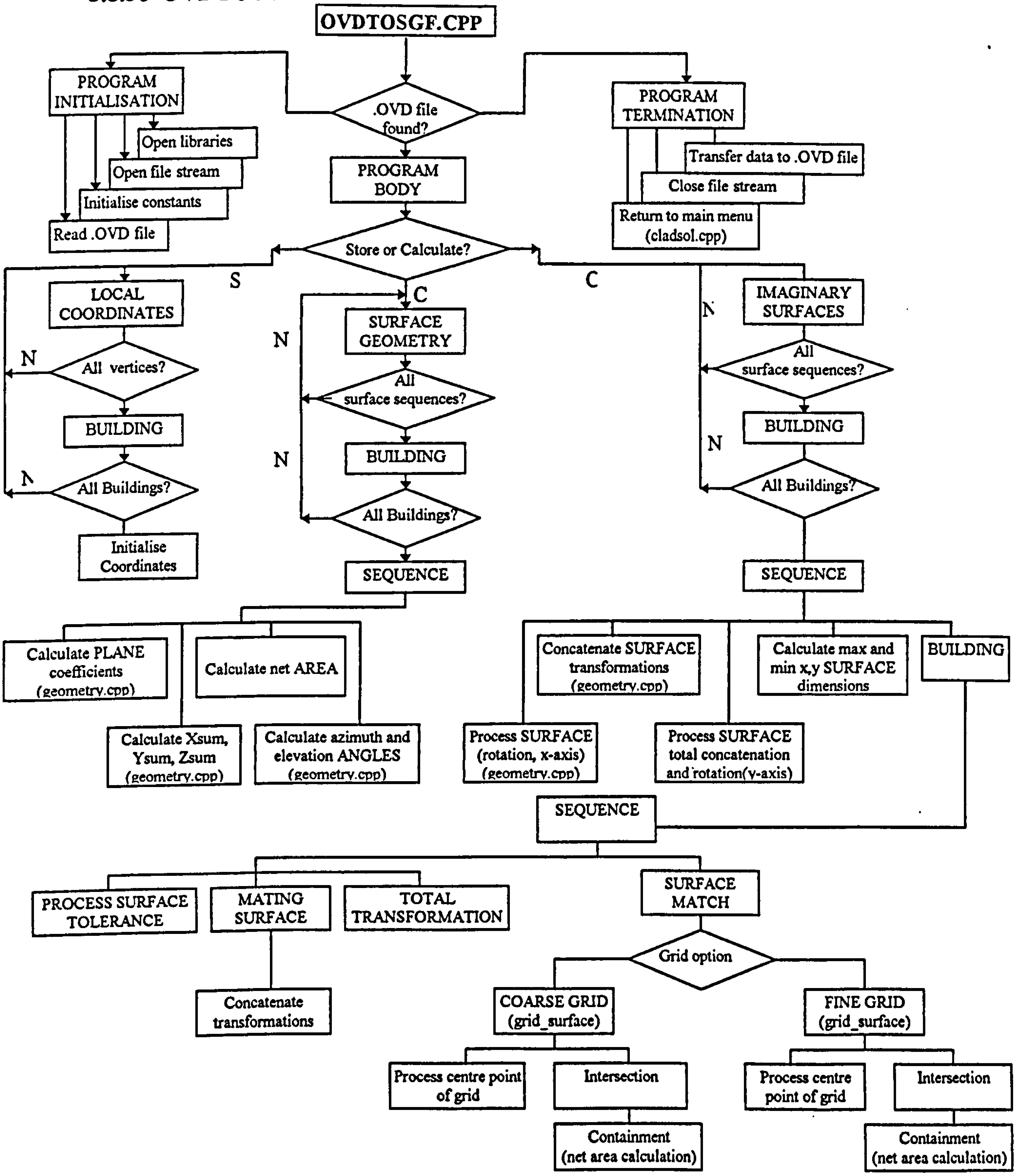

Figure 3.18: OVDTOSGF.CPP Structured Chart

This module transfers building data from the .OVD file into a binary .SGF file. It also calculates the angles of orientation and the building surface areas using trapezoidal summation and the geometrical algorithms established in section 3.4. The equation 3.24 gives the coordinates of a given surface of the building. Equation 3.25 is then used to calculate the area of the surface. The orientation of the surface is given by the azimuth angle which is calculated from equation 3.27. It also carries out the identification of hidden surfaces by establishing line intersections using polygon containment tests through the use of equations 3.35 and 3.37.

3.5.3d SOLAR.CPP

The structured chart of solar.cpp follows

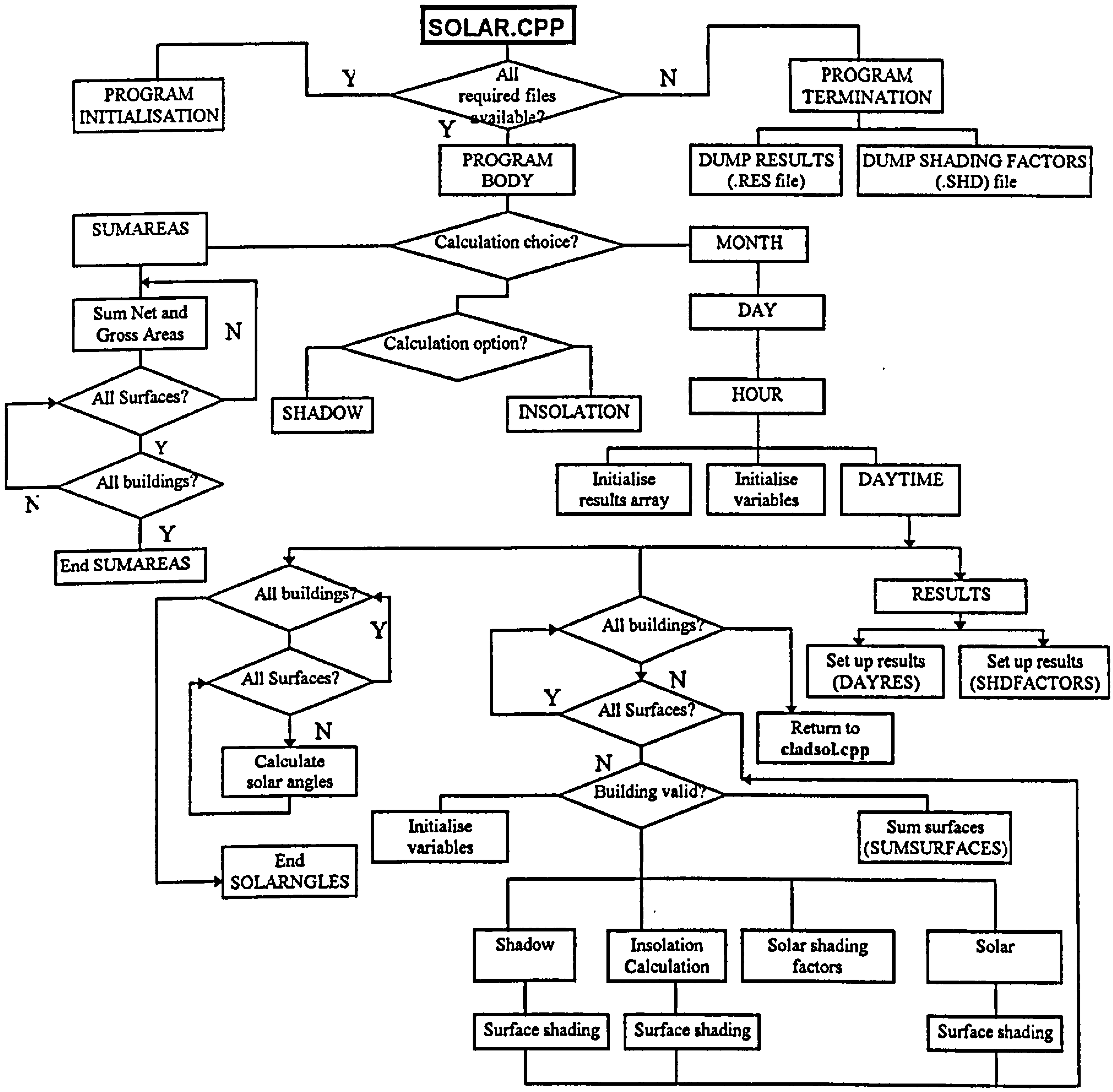

Figure 3.19: Structured chart of SOLAR.CPP

This calculates the solar angles, the solar radiation incident on the building walls using the algorithms mentioned in Section 3.3, that is, equations 3.13 and 3.16 for the isotropic model and Hay and Davies model. It also calculates the surface interference shading by using again equation 3.34 to calculate the coordinates of the surface interference.

3.5.3d Calculating PV Output

For individual consideration of the exemplar buildings, the vertex coordinates were manually put into the vertex(.OVD) file. A preliminary estimation of the possible PV power output was also considered. In section 2.3.3b preliminary array sizing equations were discussed. Since there was no limitation of the load to be powered by the plant the Area method was therefore used. In equation 2.24

$$P_A = E_e \cdot \cos\Gamma \cdot \eta \cdot F \cdot A_a$$

the following substitutions were made

the incident solar radiation S = $E_e \cos\Gamma$

efficiency and degradation $\eta F = \eta_{BOS}\eta_{MOD}\eta_T FF$.

The estimated output of a PV array is then given by

$$P = A.S.\eta_{BOS}.\eta_{MOD}.\eta_T.FF$$

The product of area and solar radiation, A.S, is obtained from the Solar.cpp module calculations. The balance of system efficiency was taken to be, η_{BOS} = 85%.

Module efficiency, η_{MOD} is taken as 18%(assumed to be commercially available at the turn of the century). Decreasing factor due to temperature, dust, array mismatch, η_T is assumed to be 90%. Fill factor, FF, is assumed to be 80% which is near to the present BP585 module. The potential of the installed PV modules is considered in Section 3.6 and the preliminary PV output for the months with the highest and least solar energy values is shown in Figures 3.31 to 3.44. The results are given normalised with respect to the external area of the whole building.

3.6. Building-Integrated PV on Exemplar Buildings

3.6.1 The Business Hotel

This is an arc-shaped 19-storey building. Each floor has an external wall height of 3m. The areas available for photovoltaics are the cladded areas of the walls.

The PV system was considered to consist of the high performance BP585 monocrystalline modules whose dimensions are illustrated below in Figure 3.21. For optimal orientation of the modules in the benchmark city, whose latitude is 17.5° the modules have to be installed at 17.5° facing northwards. Consequently the length of vertical wall required is 0.35 metre and this can be accommodated by the height of the non-window portion of the external wall on each floor, which is 0.8 metre. The external wall of each floor can hold 1 row of modules. The cross section of the installed modules on the north facing wall are illustrated in Figure 3.22

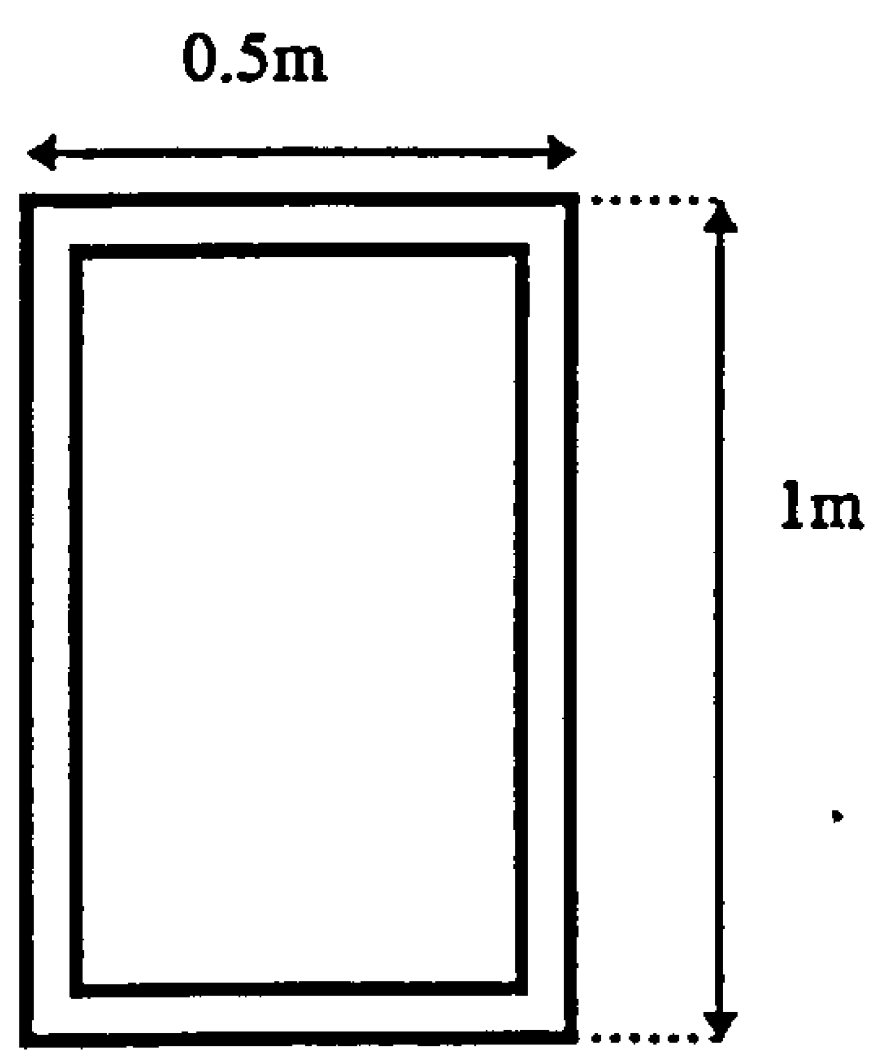

Figure 3.21: BP585 Monocrystalline Solar Module

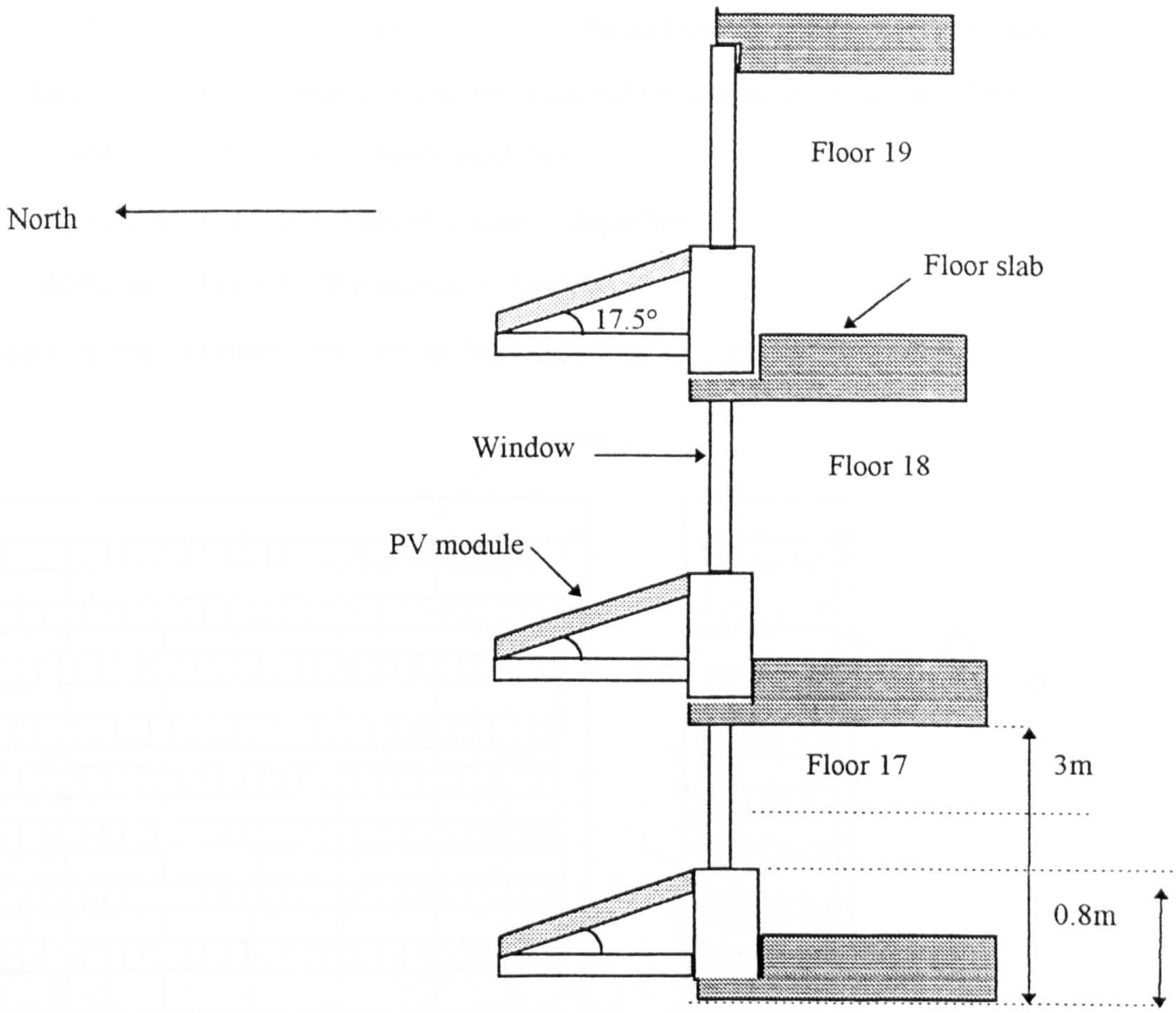

Figure 3.22: Modules Integrated into North Facing Wall

Although the building has 19 floors, its construction with a pool deck on the second floor level, and trees around it means that only the non-window areas on 16 of the floors are suitable for PV cladding. On the front wall 74.5 metres of wall length is available for PV cladding. On the back wall, 85.5 metres wall length is available for cladding with PV . On the side walls 7.5m length of wall is available for cladding.

Therefore, giving an allowance of 0.6m of module width

The number of modules that can be installed on the north wall is

16 rows × (74 metres per row ÷ 0.6metres per module) = 1968 modules

The number of modules on that can be installed on the back wall is

16 rows × (85.5 metres per row ÷ 0.6 metres per module) = 2272 modules

The number of modules on that can be installed on the side wall is

16 floors × (8.0 metres per row ÷ 0.6 metres per module) = 200 modules

The total number of modules that can be installed on the building is therefore

1968 + 2272 + 400 = 4640 modules

This is equivalent to a plant with an installed capacity of

4640 modules × 85 W/module = 394kW$_p$

The view of the modules view are as shown in Figure 3.24

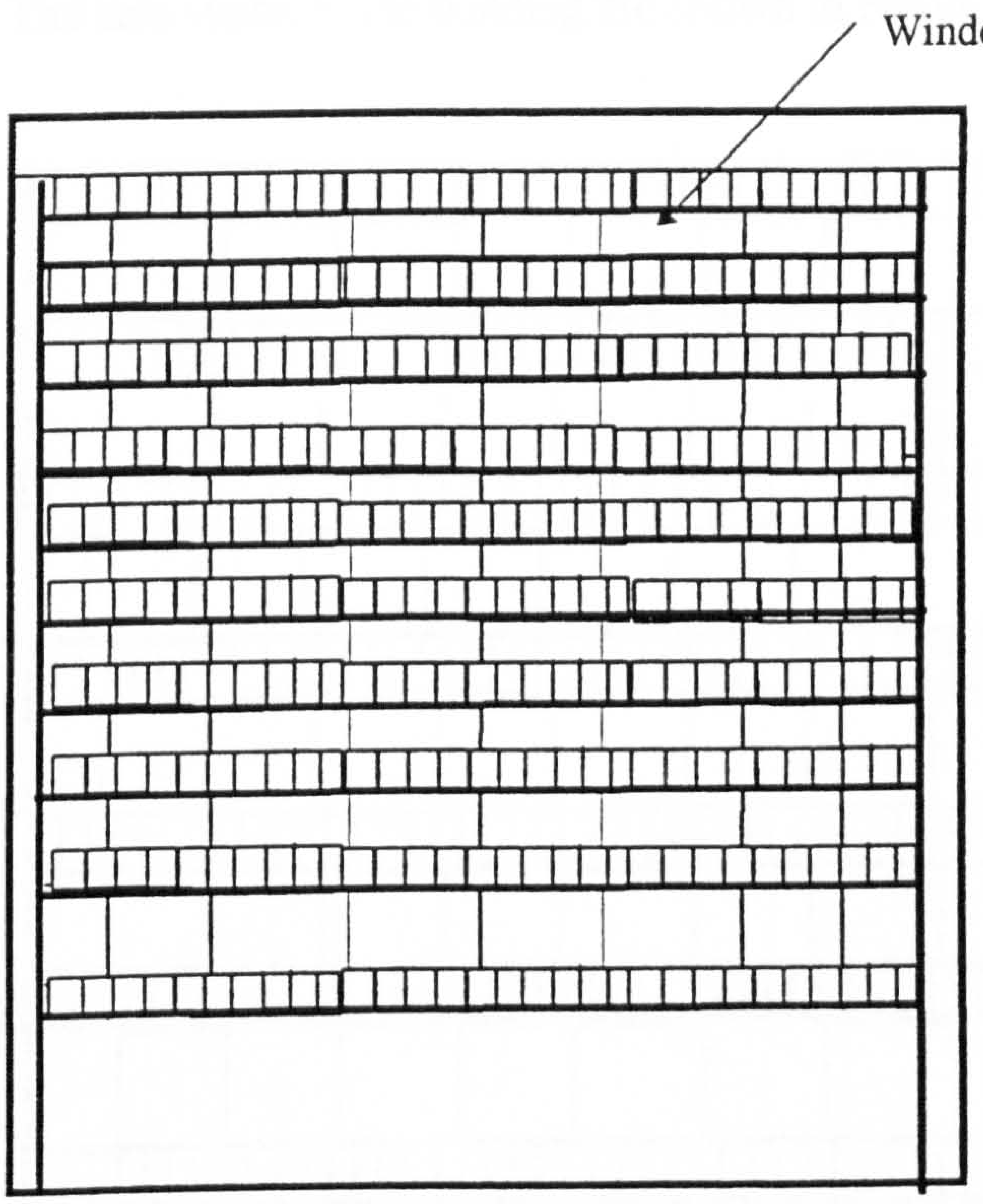

Figure 3.24a The view of the modules on the North Wall of the Business Hotel

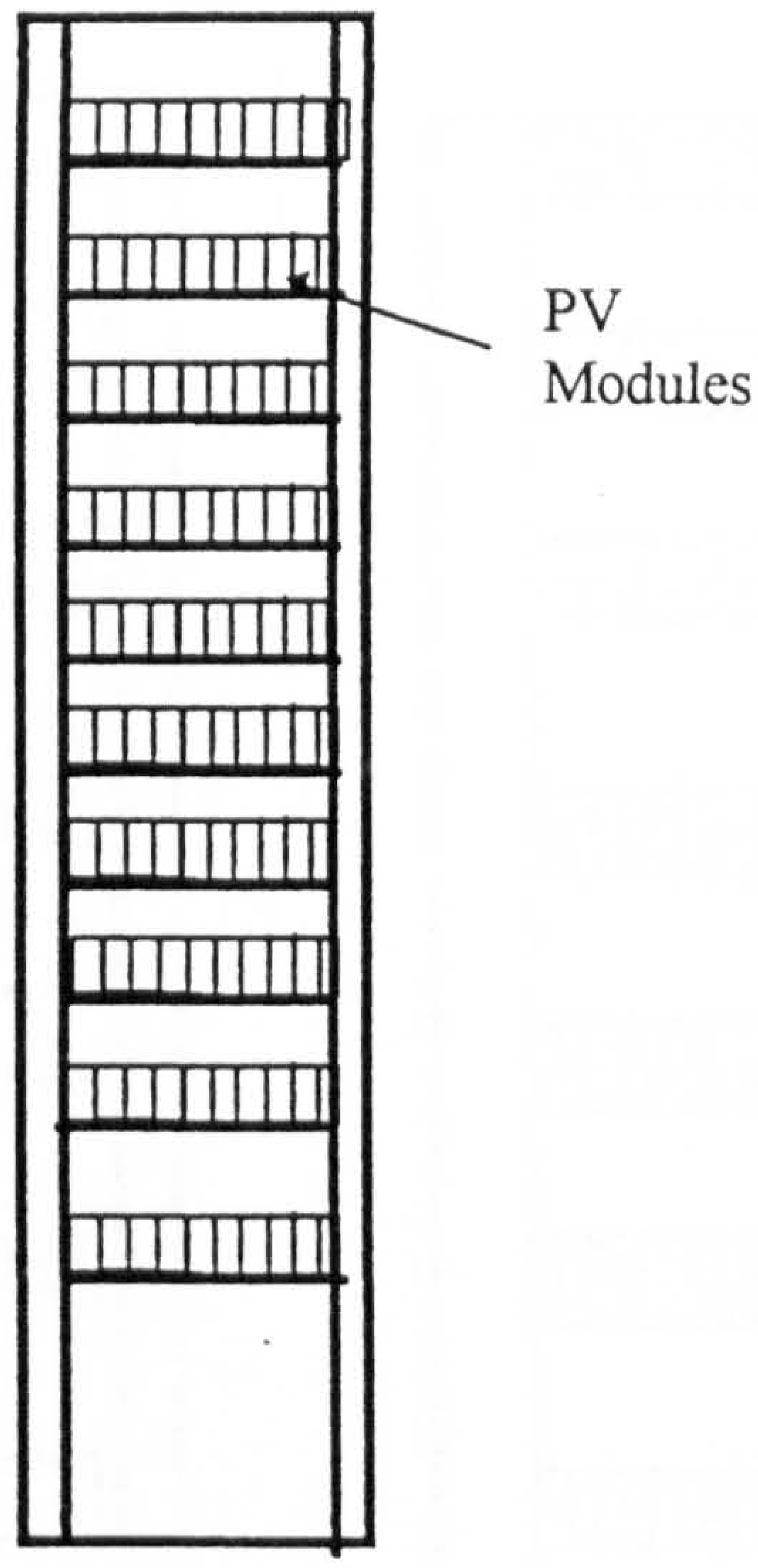

Figure 3.24b: The view of the module Side View

3.6.2 The Non-Air-Conditioned Government Office Building

This is a 20 storey government office building with an east west orientation constructed in the late 1970s and located on the north west outskirts of Harare city centre. Considering the same design illustrated in Figure 3.22a and Figure 3.22b, then the potential number of modules that can be installed on the walls of the building can be estimated as follows. The modules that can be installed on the north facing and south facing walls are

20 rows × (86 metres per row ÷ 0.6metres per module) = 2860 modules

This is equivalent to an installed capacity of 2860 modules × 85W = 243.1 kW$_p$

The modules that can be installed on the east and west facing walls are

$$20 \text{ rows} \times (20 \text{ metres per row} \div 0.6 \text{metres per module}) = 660 \text{ modules}$$

This is equivalent to an installed capacity of 660 modules × 85W/module = 56.1 kW_p

This would give a total of (2860 × 2) + (660×2) = 7040 modules

This is equivalent to an installed capacity of

$$7040 \text{ modules} \times 85\text{W/module} = 598.4 \text{ kW}_p$$

The side views of the building are shown in Figure 3.25 and Figure 3.26

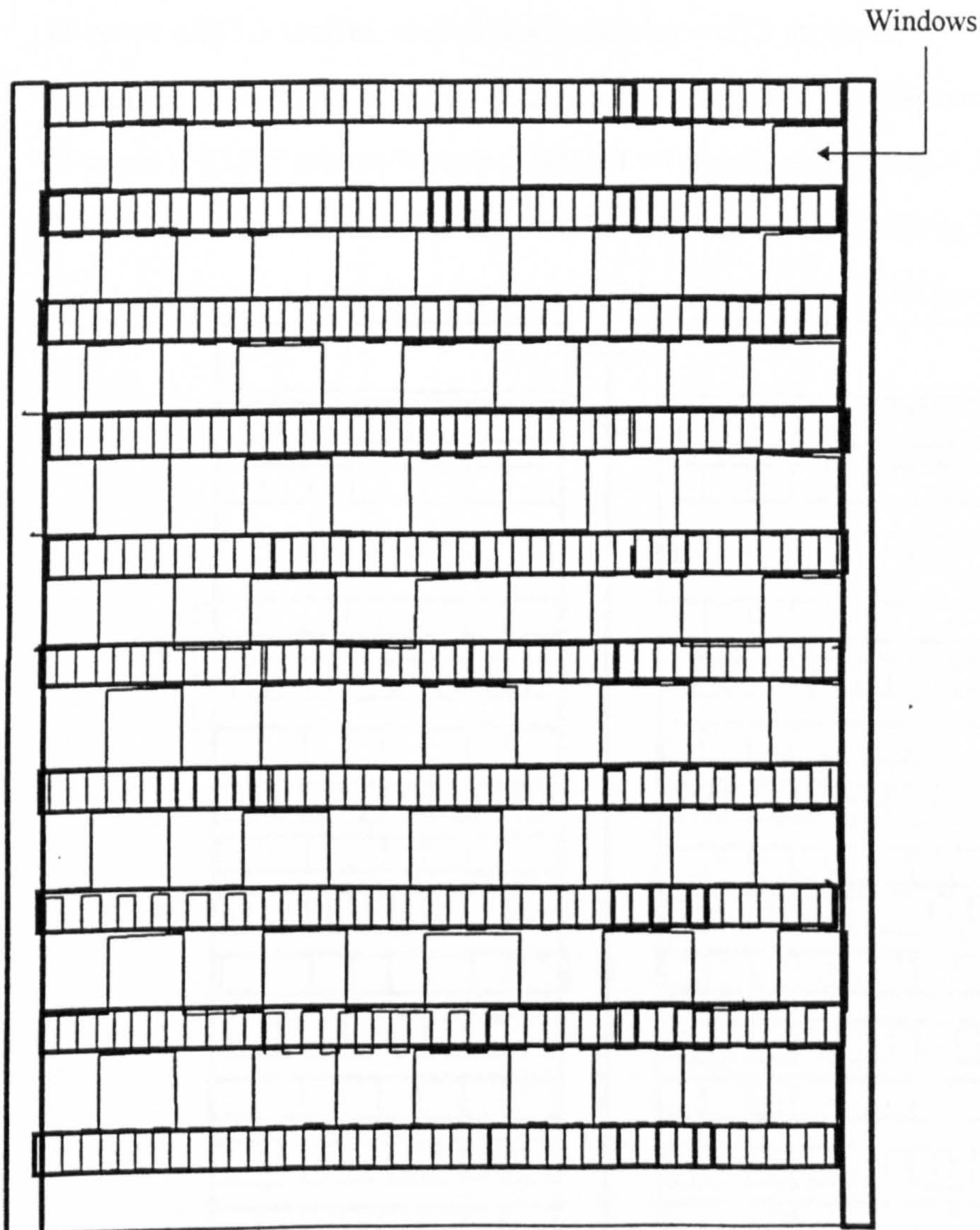

Figure 3.25 View of PV Modules on Front Wall

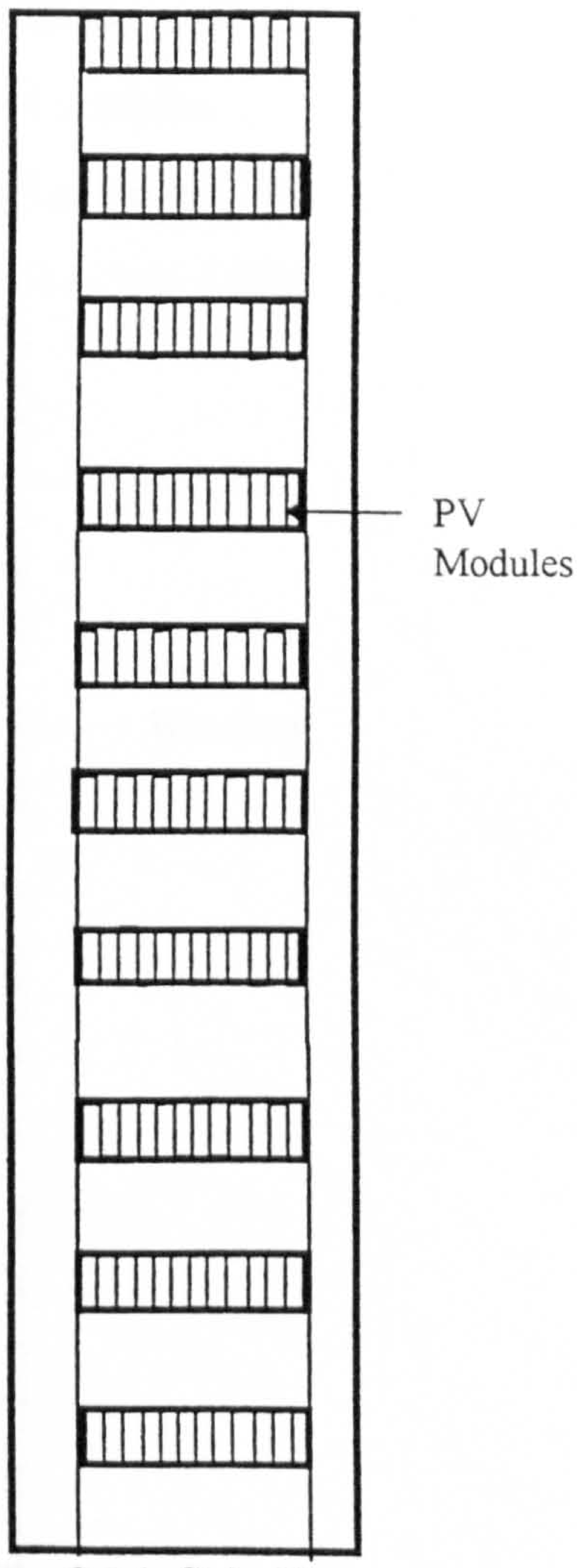

Figure 3.26: Side View

3.6.3 The Tenant Occupied Executive Commercial Building

This is a 17-storey building. Its dimensions are shown in the side views in Figures 3.27, which also show the position of the modules. 16 rows of modules can be installed on the walls . Therefore the potential number of modules that can be installed on the north and south facing walls are

16 rows × ((18.6metres/wing × 2 wings) ÷ 0.6metres/module) = 992 modules

The potential number of modules a that can be installed on the east facing wall is

16 rows × (25.3 metres ÷0.6 metres/module) = 672 modules

The potential number of modules a that can be installed on the west facing wall are

16 rows × ((10.5 metres/wing × 2 wings) ÷ 0.6metres/module) = 544 modules

The total number of modules that can be installed on the building is therefore 4240.

This would give an installed capacity of 4240 modules × 85W/module = 360.4 kW_p

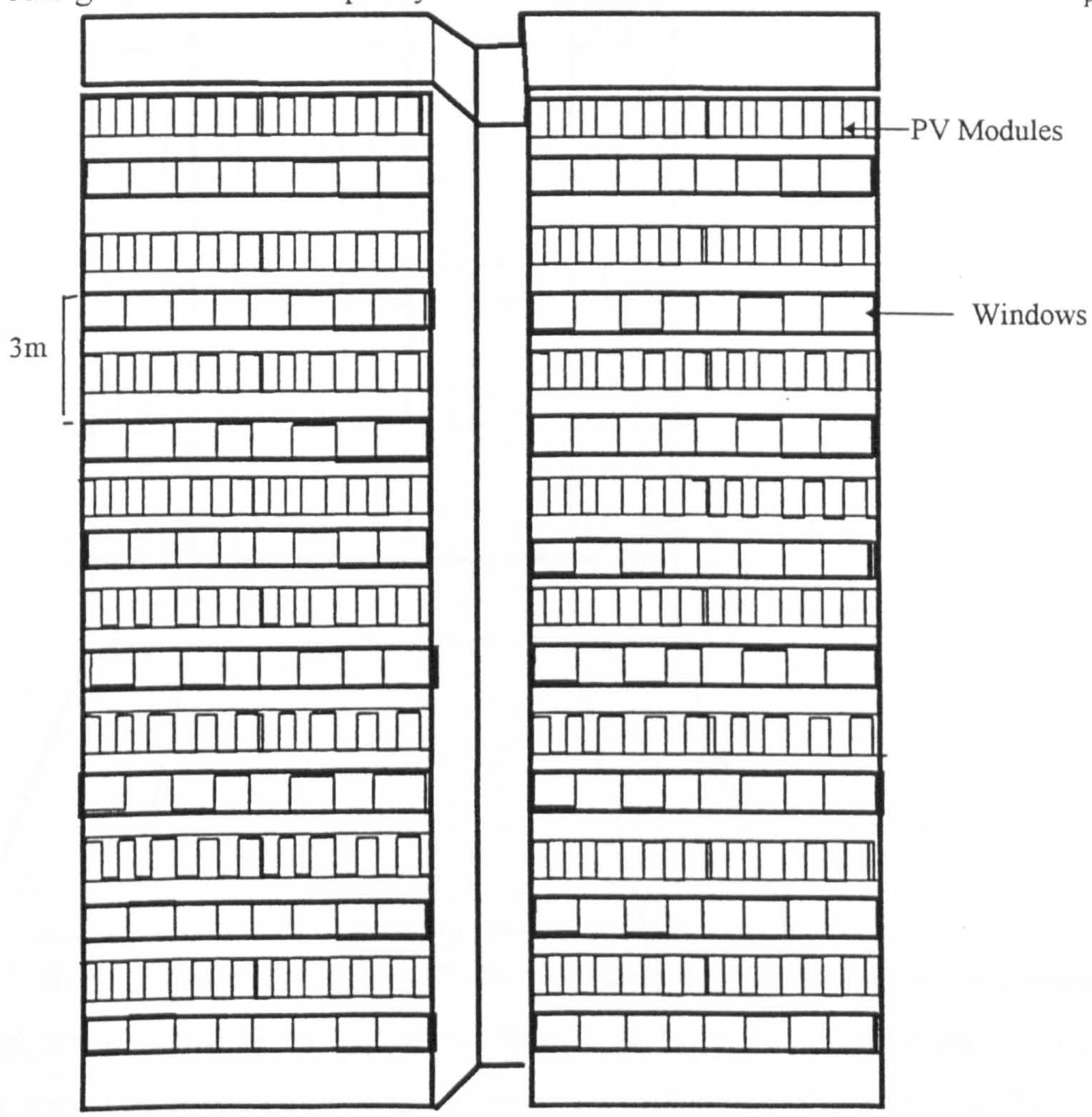

Figure 3.27 The view of the modules on the side walls

3.6.4 The Prestige Modern Commercial Office Building

This is an octagonal twenty-six storey building with the sixth floor to the twenty sixth floor entirely covered by a glass curtain. The ground floor to fifth floor, however, have polished granite cladding around their walls instead of the glass curtain.

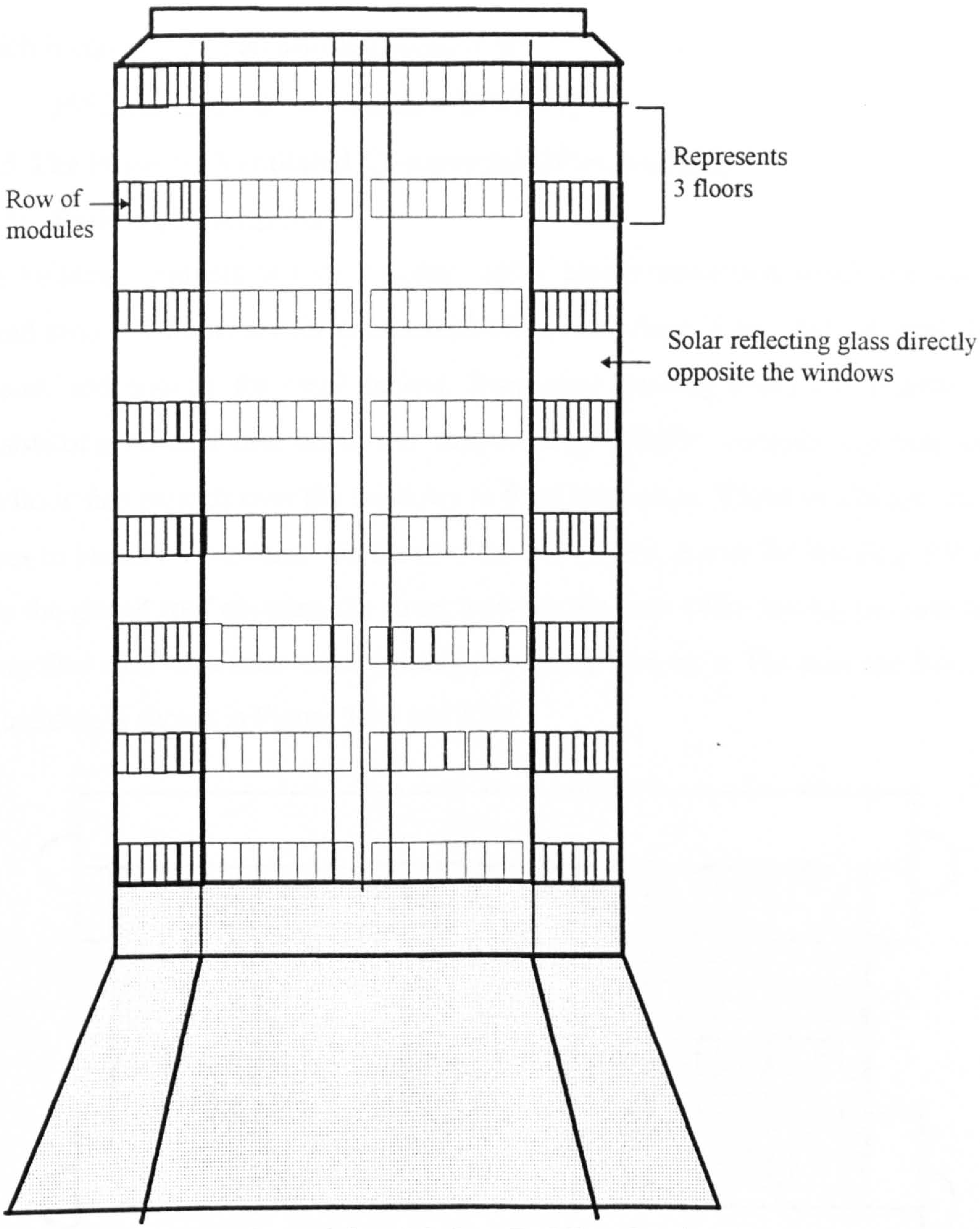

Figure 3.28: Side View of Prestigious Modern Building showing the position of the modules

The design is such that any modules that have to be integrated into the building have to be part of the curtain and must not occupy the area directly in front of the windows. Therefore only a third of the curtain wall area is available for installing PV modules, and only 21 rows of modules can be installed on each wall. The possible arrangement of PV modules integrated into one of the glass curtain walls is shown in Figure 3.28. The potential of number of PV modules that can be installed on the buildings is estimated as follows. Considering the 8 walls

$$8 \text{ sides} \times 21 \text{ rows/sides} \times (10.2 \text{ metres} \div 0.6 \text{ metres/module}) = 2856 \text{ modules}$$

Which is equivalent to an installed capacity of

$$2856 \text{ modules} \times 85 \text{ W/module} = 242.7\text{kW}_p$$

3.6.5 The Passively Ventilated Commercial Office Building

3.6.5a. Building Description

This building consists of two 9-storey office blocks orientated which are joined by a glazed atrium. 7 floors are for commercial offices and there is one parking level above the ground, and another for retail outlets. Two other parking levels are underground.. It consists of a 9 inch double brick wall supported by 450,000 mullions of precast concrete. The floor slab extends over the windows to form overhangs. These overhangs are suitable places to install PV modules. On the roof the most suitable area for installing PV modules is on the glazed roof covering the street between the twin office blocks, because the north facing tiled roof have solar water heating panels installed on it. The plan and front view of the building is shown in Figure 3.29 and 3.30.

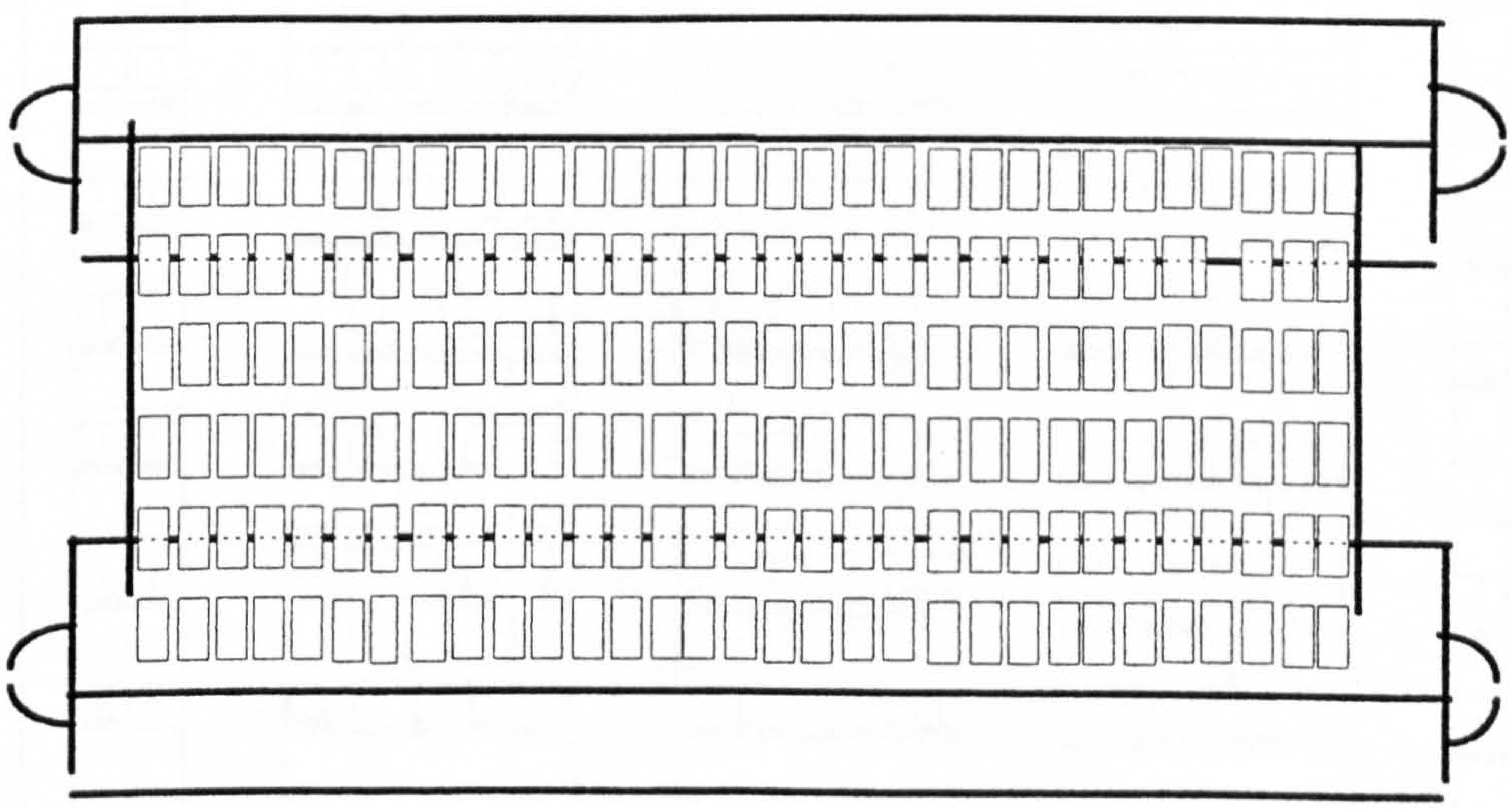

Figure 3.29: Roof View of Passively Ventilated Building showing the position of the modules

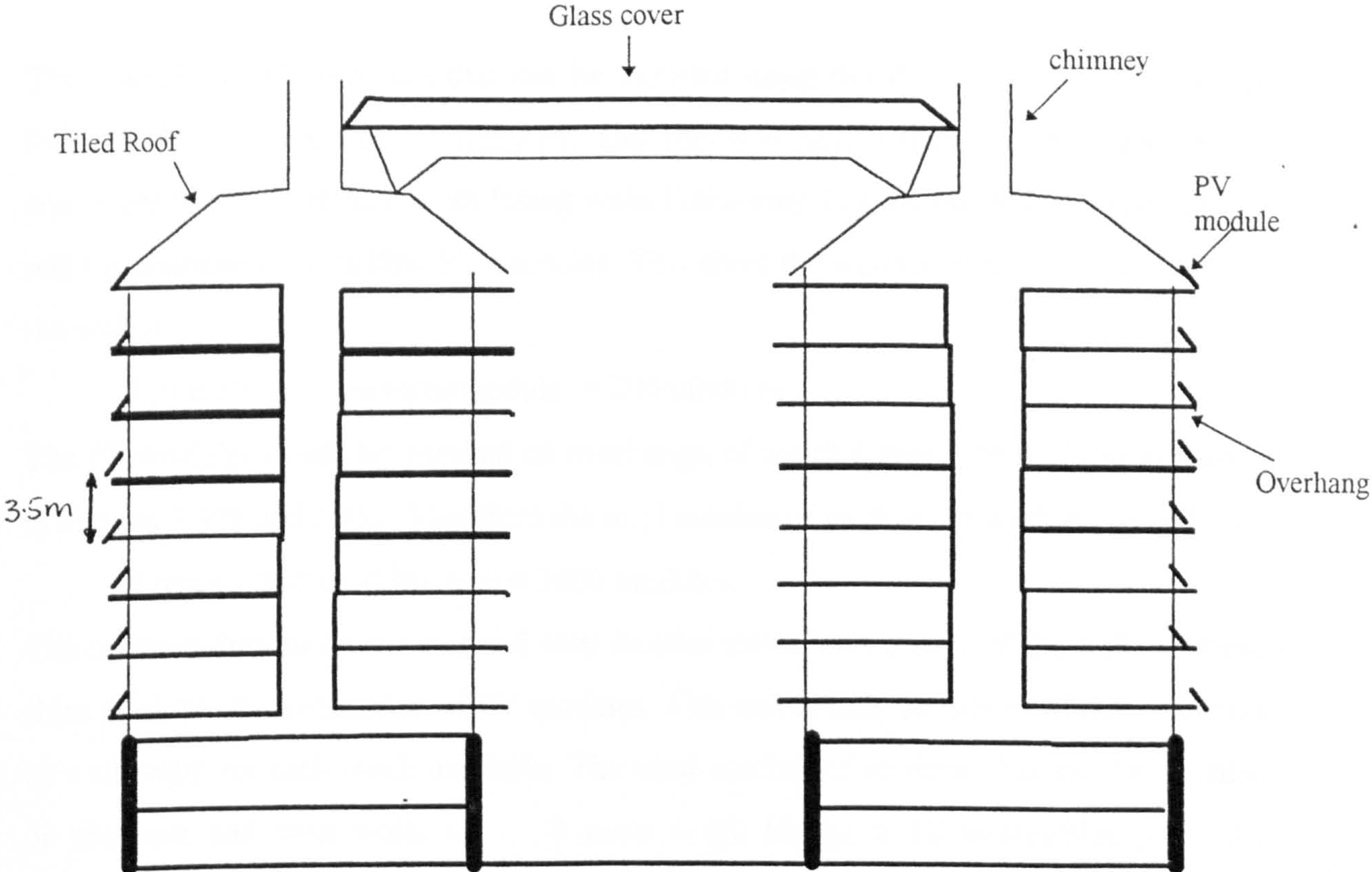

Figure 3.29a Cross Section of Passively Ventilated Building showing the position of the PV Modules on The Overhangs

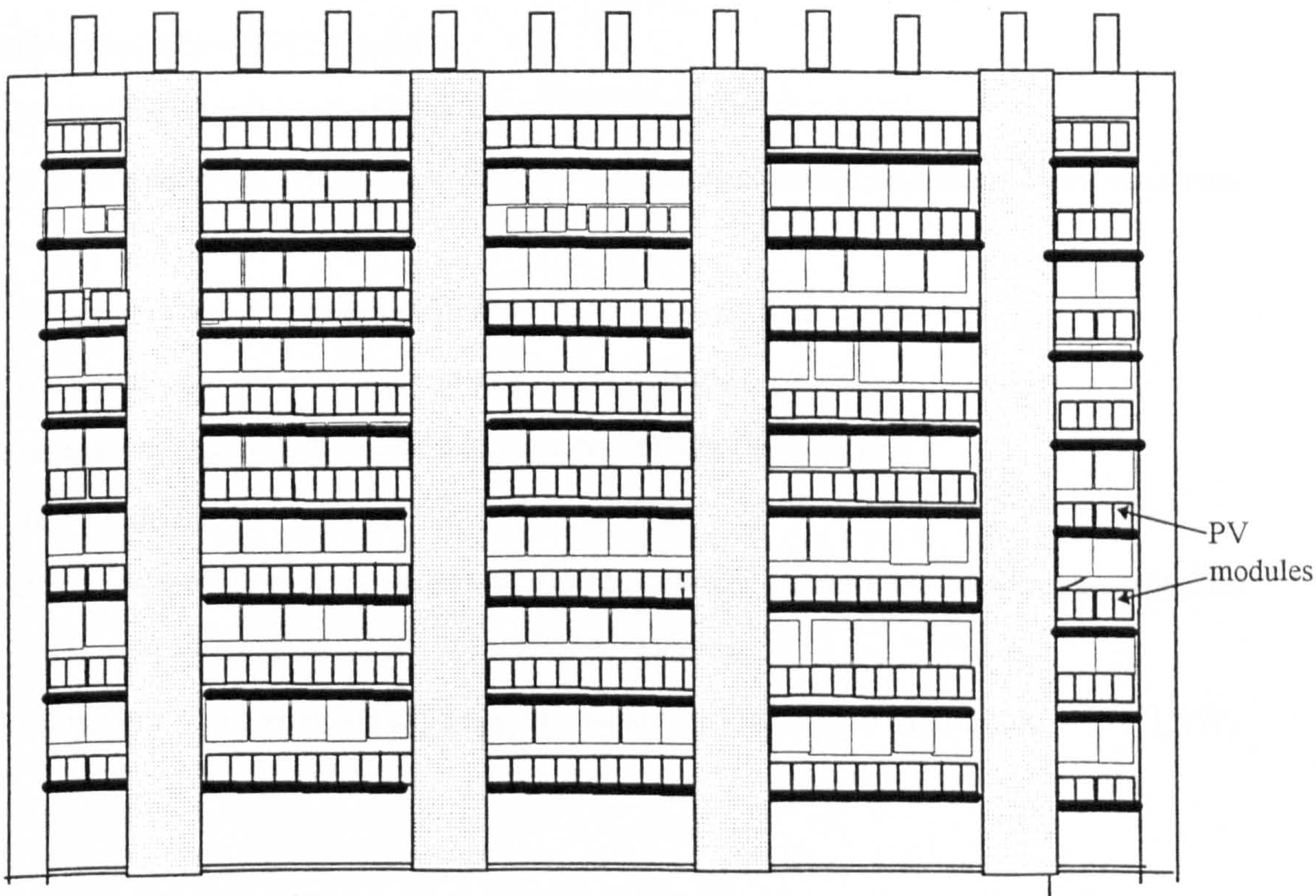

Figure 3.29b:North View of Passively Ventilated Building showing the location of the modules

The potential of PV modules that can be installed using this design can be estimated as follows: The presence of 4 stairwells and the interruption their design make on the continuity of the north and south facing walls limits only 119 metres of 140 metres length will be available for installing PV modules. This gives the number of modules in a row on the wall is

$$119 \text{ metres} \div 0.6\text{metres/module} = 200 \text{ modules}$$

The PV modules would be installed on overhangs, of which 8 levels are available as shown in Figures 3.30b and 3.30c. Therefore the total number of modules on each face would be

$$8 \text{ rows} \times 200 \text{ modules/row} = 1600 \text{ modules.}$$

The concrete designs on the east and west facades makes only a third of the walls on these sides available for installation of PV modules. This makes only 10 metres of the 16 metres of wall width on each block available. The total number of modules that can be installed on the east and west walls is: $8 \text{ rows} \times ((2 \text{ blocks} \times 10 \text{ metres/block}) \div 0.6 \text{ metres/modules}) = 256 \text{ modules}$

The total number of modules that can be installed on the walls on the building is therefore $(2\times1600) + (2\times256) = 3712$ modules

This is equivalent to an installed capacity of : $3712 \times 85 = 315.5 \text{ kW}_p$

112 metres of glass roof length and 42metres width is available and this allows each row to have

$$(42 \text{ metres} \div 1.5 \text{ metres/module}) = 28 \text{ rows each with}$$

$$(112 \text{ metres} \div 0.6 \text{ metres/module}) = 186 \text{ modules}$$

The number of modules that can be installed on the roof is therefore

$$186 \text{ modules/row} \times 28 \text{ rows} = 6524 \text{ modules}$$

The glazed roof would increase substantially the number of modules that can be installed as follows: $6524 \text{ modules} + 3712 = 10236 \text{ modules}$

This is equivalent to an installed capacity of : $10236 \text{ modules} \times 85 \text{ W/module} = 870.1 \text{ kW}_p$

3.6.6 Results of PV Simulation

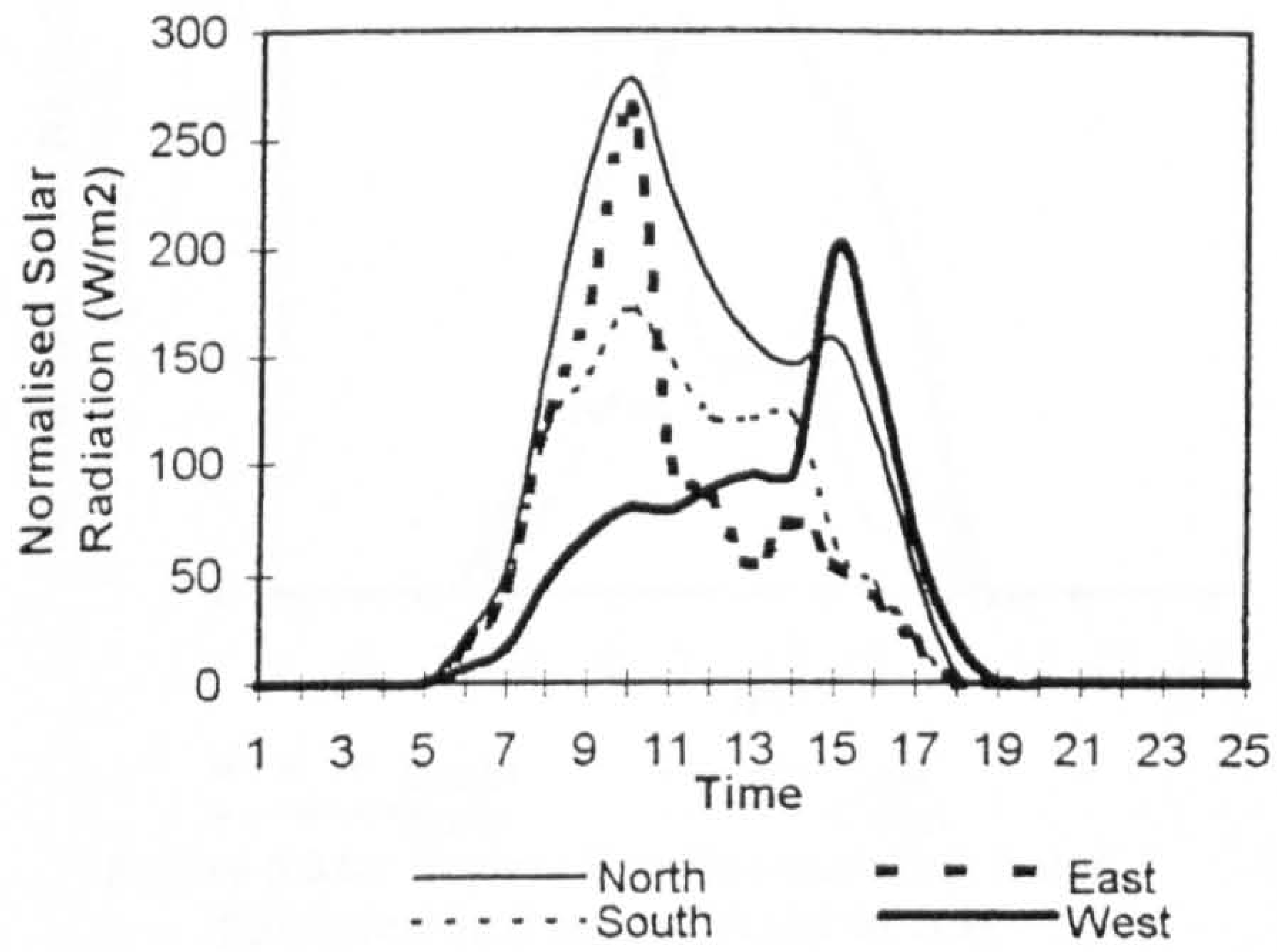

Figure 3.31a: Business Hotel, Solar Radiation on Different Facing Walls in July

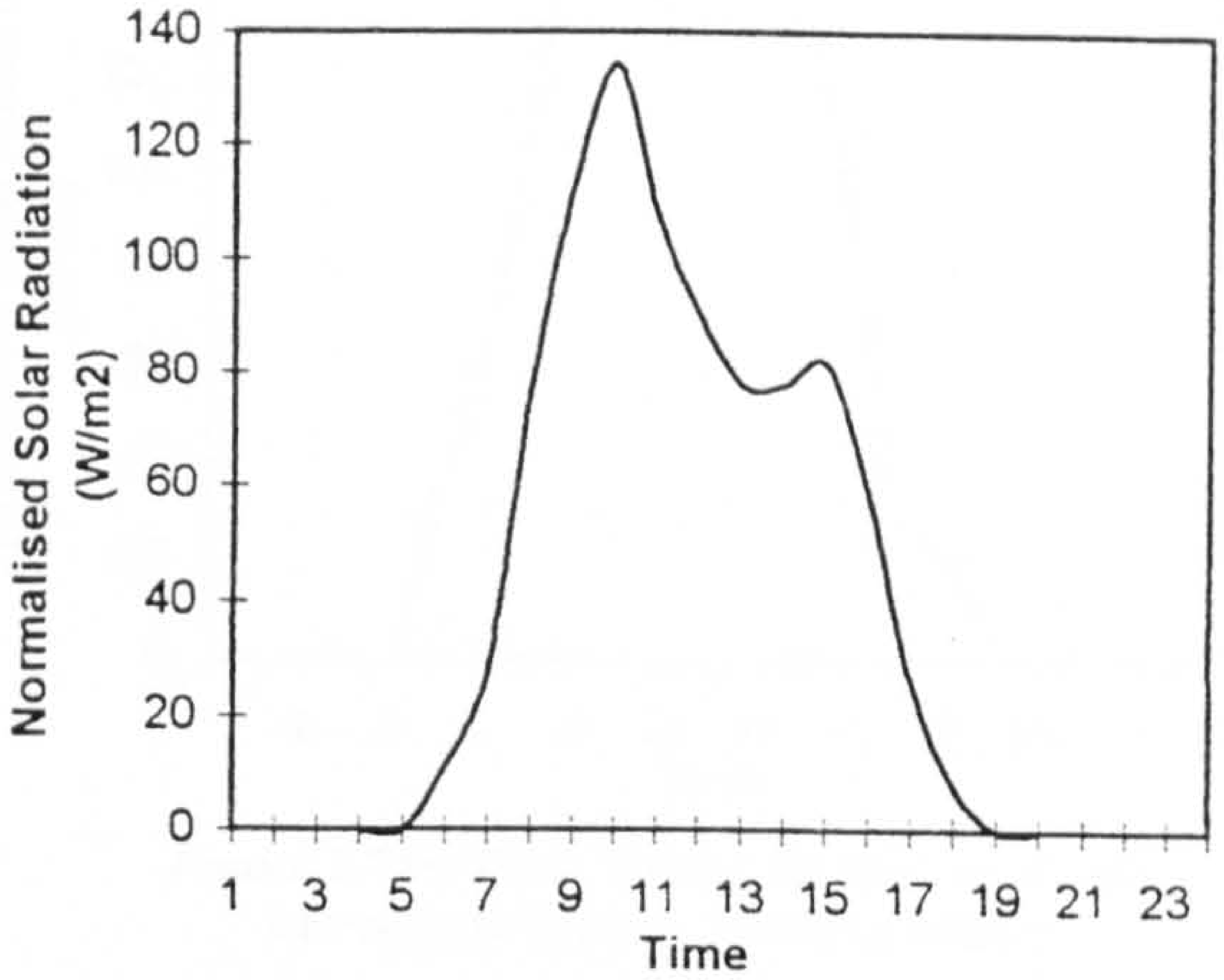

Figure 3.31b: Total Solar Radiation on Walls of Business Hotel Building in July

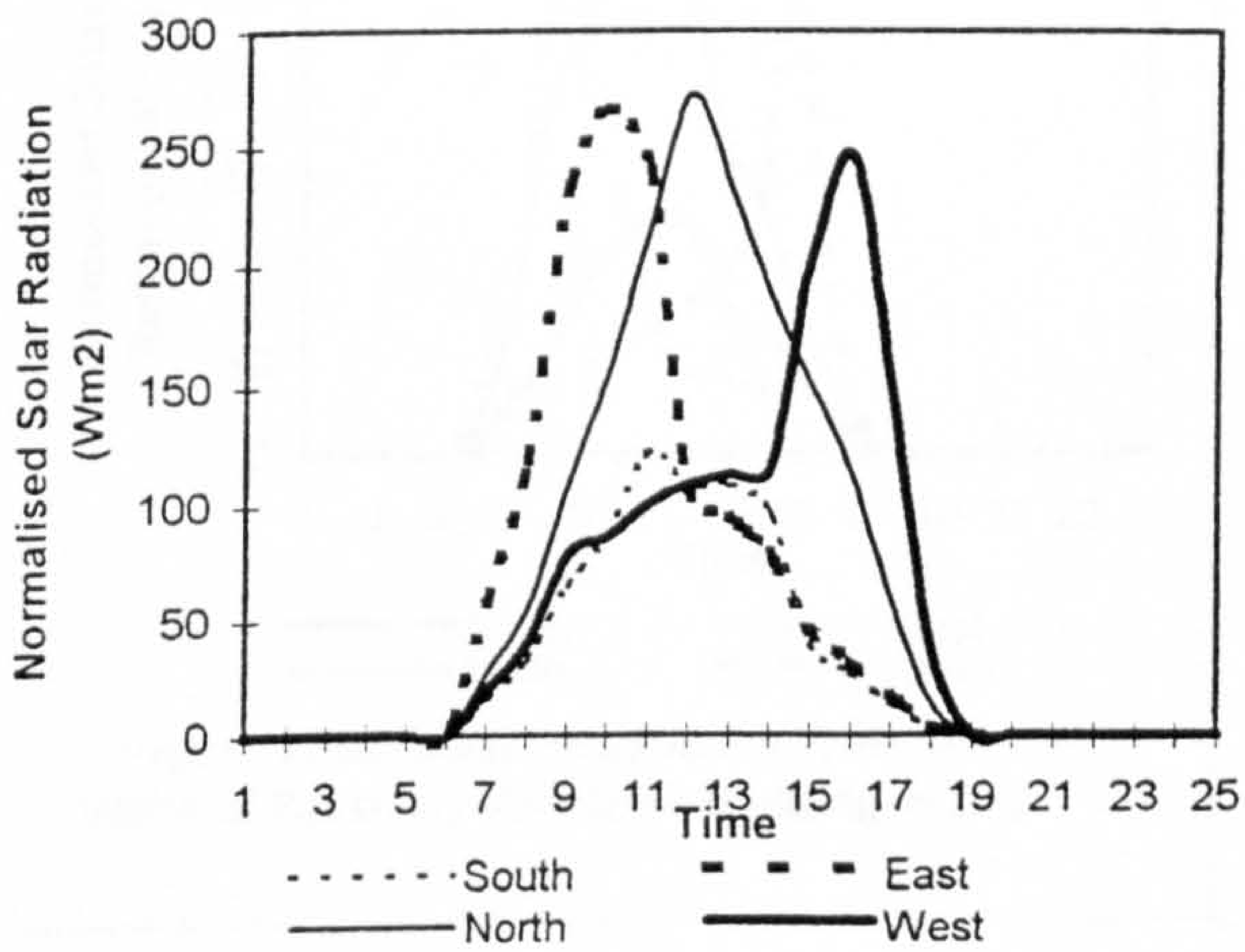

Figure 3.32a: Government Office Building, Solar Radiation on Different Walls in July

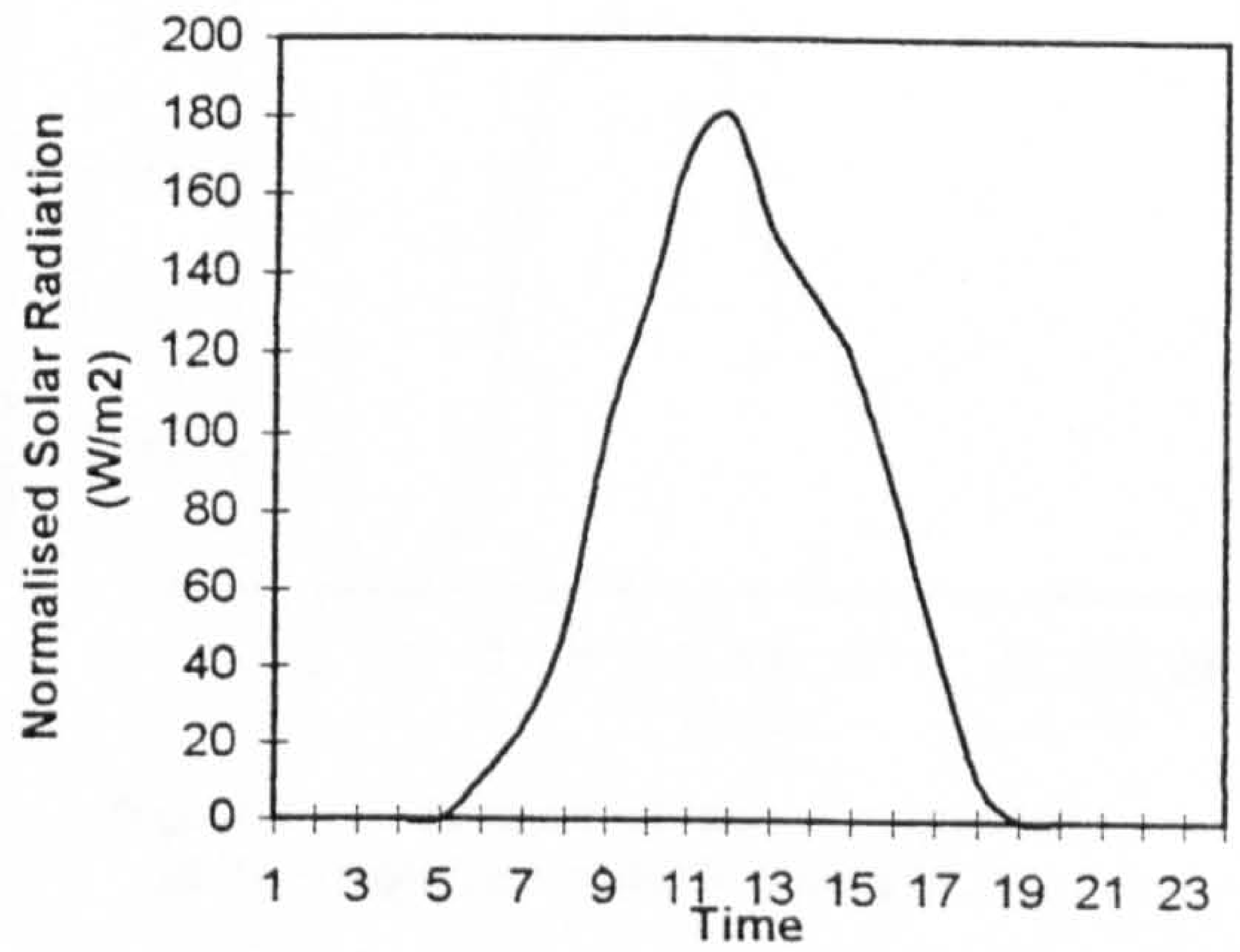

Figure 3.32b: Total Solar Radiation on Walls of Government Office Building in July

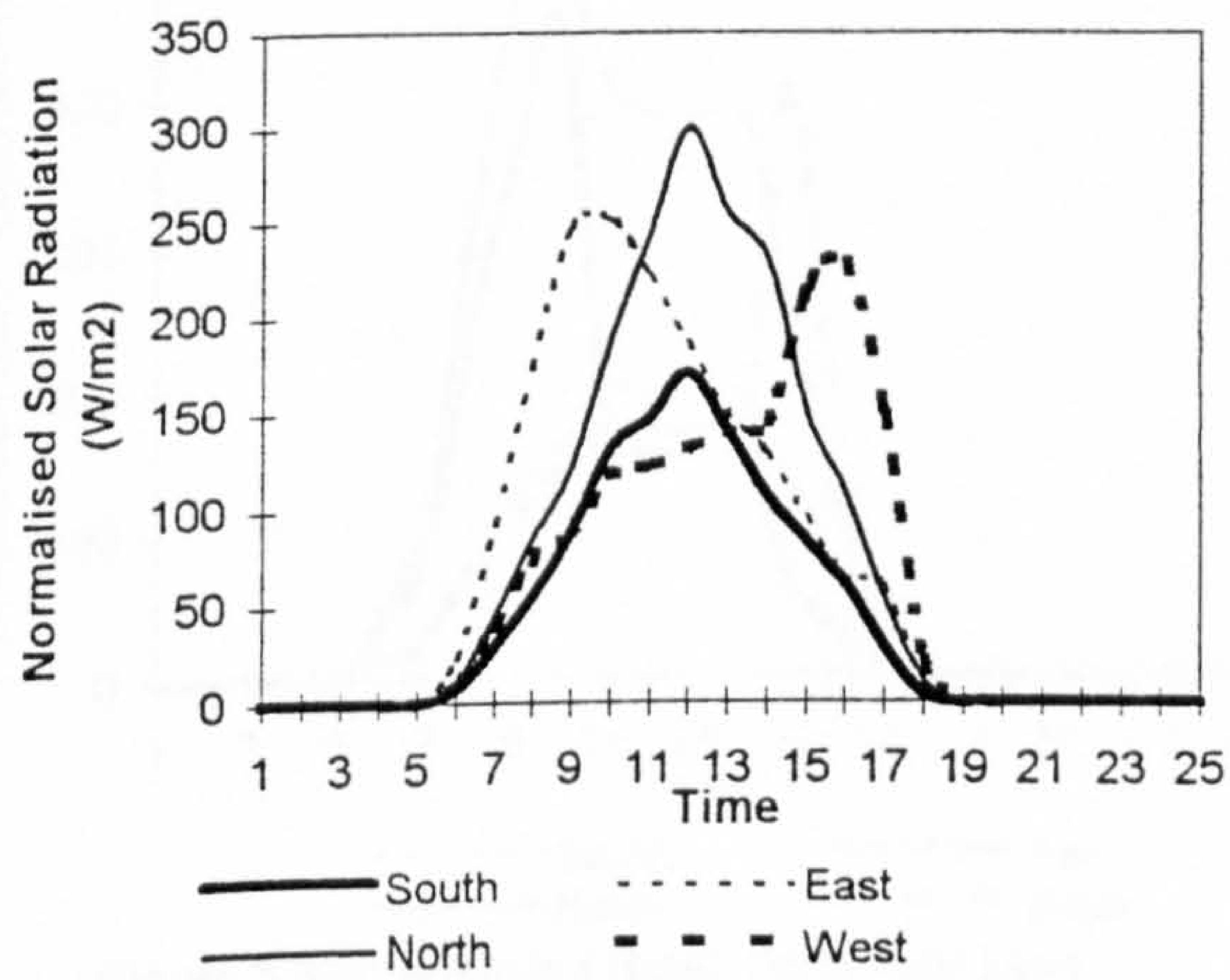

Figure 3.33a: Tenant Occupied Building, Solar Radiation on Different Walls in July

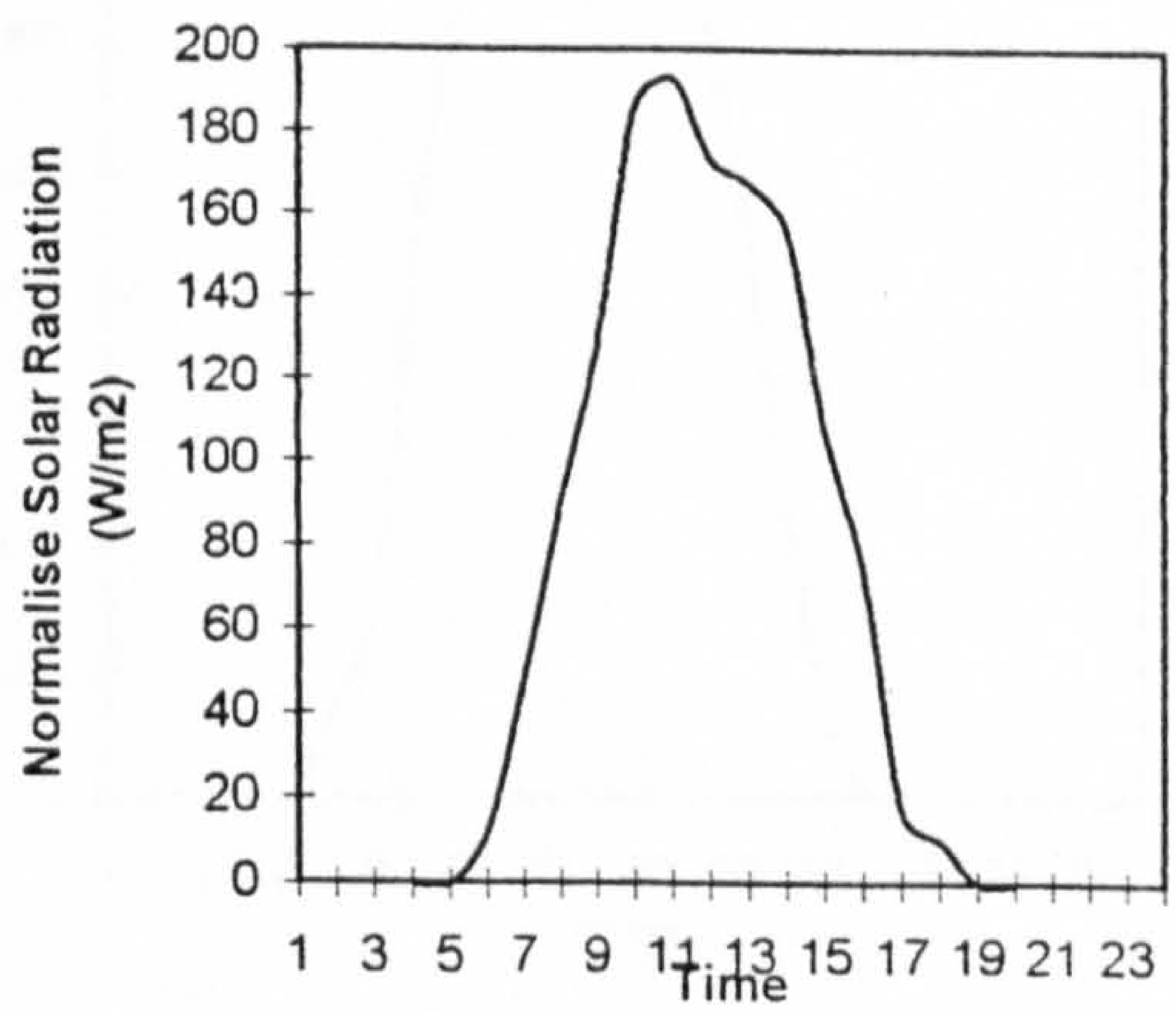

Figure 3.33b: Total Solar Radiation on Walls of Tenant Occupied Building in July

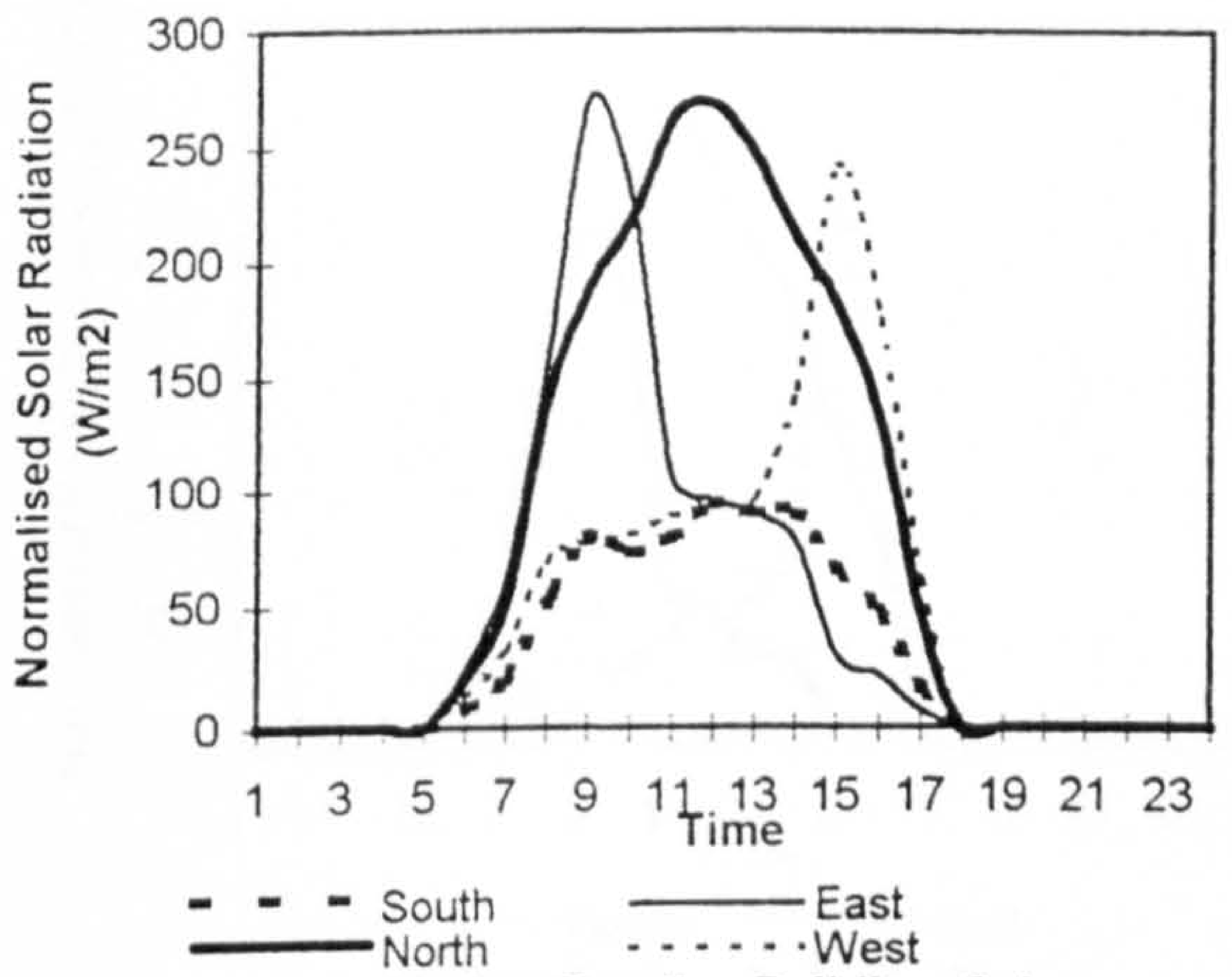

Figure 3.34a: Modern Prestige Building, Solar Radiation on Different Walls in July

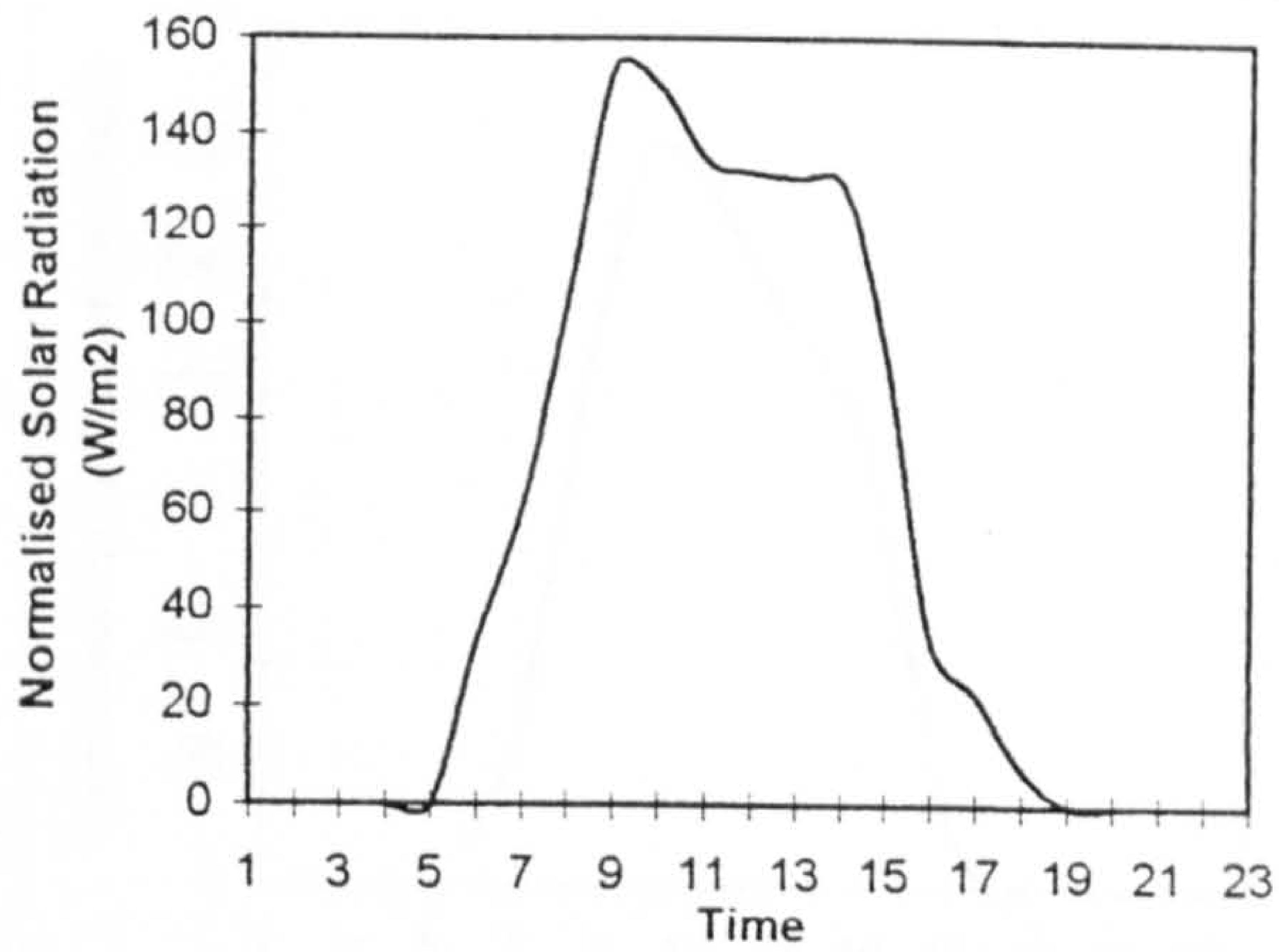

Figure 3.34b: Total Solar Radiation on Walls of Prestige Modern Building in July

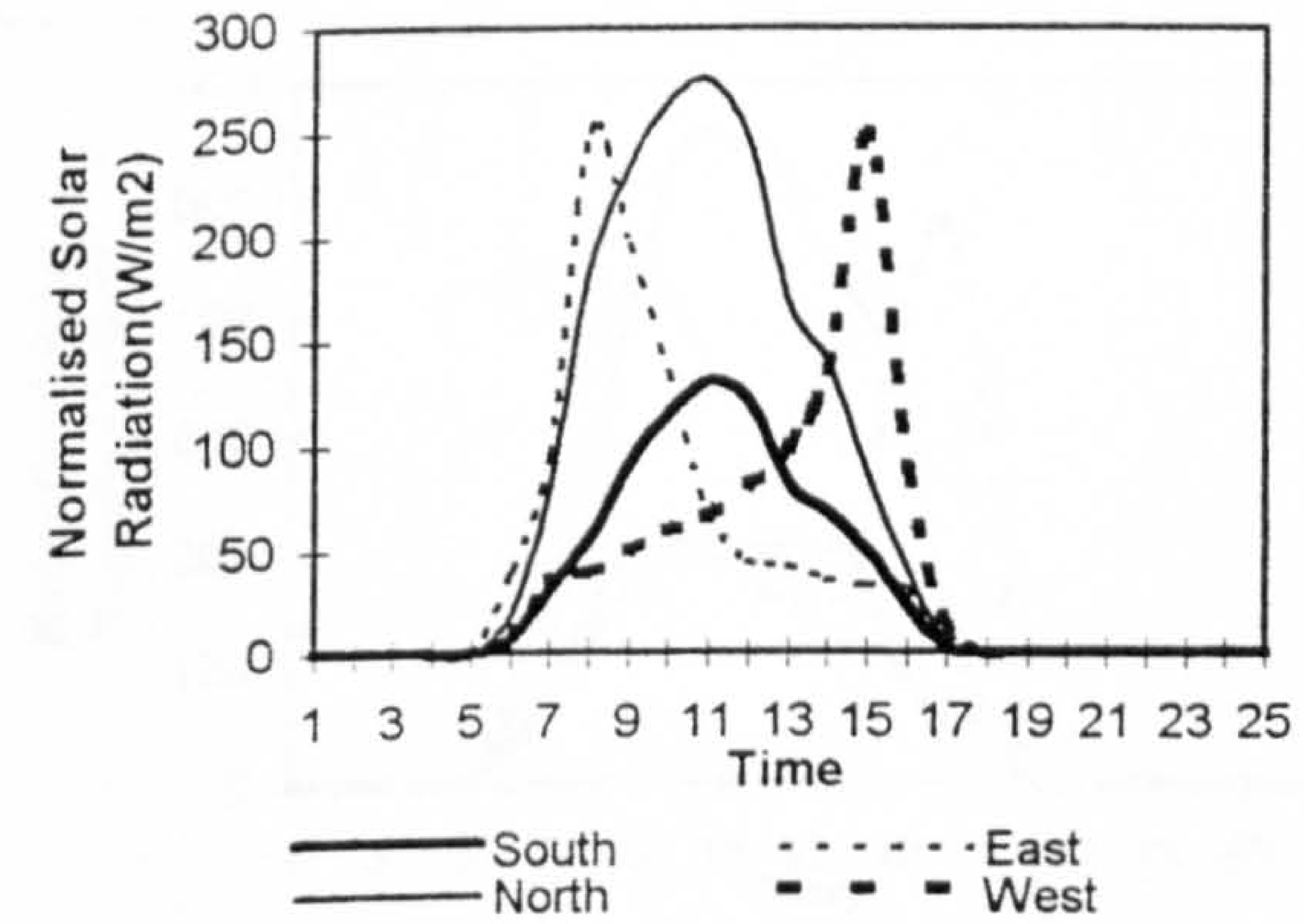

Figure 3.35a: Solar Radiation on Different Walls of Passively Ventilated Building in July

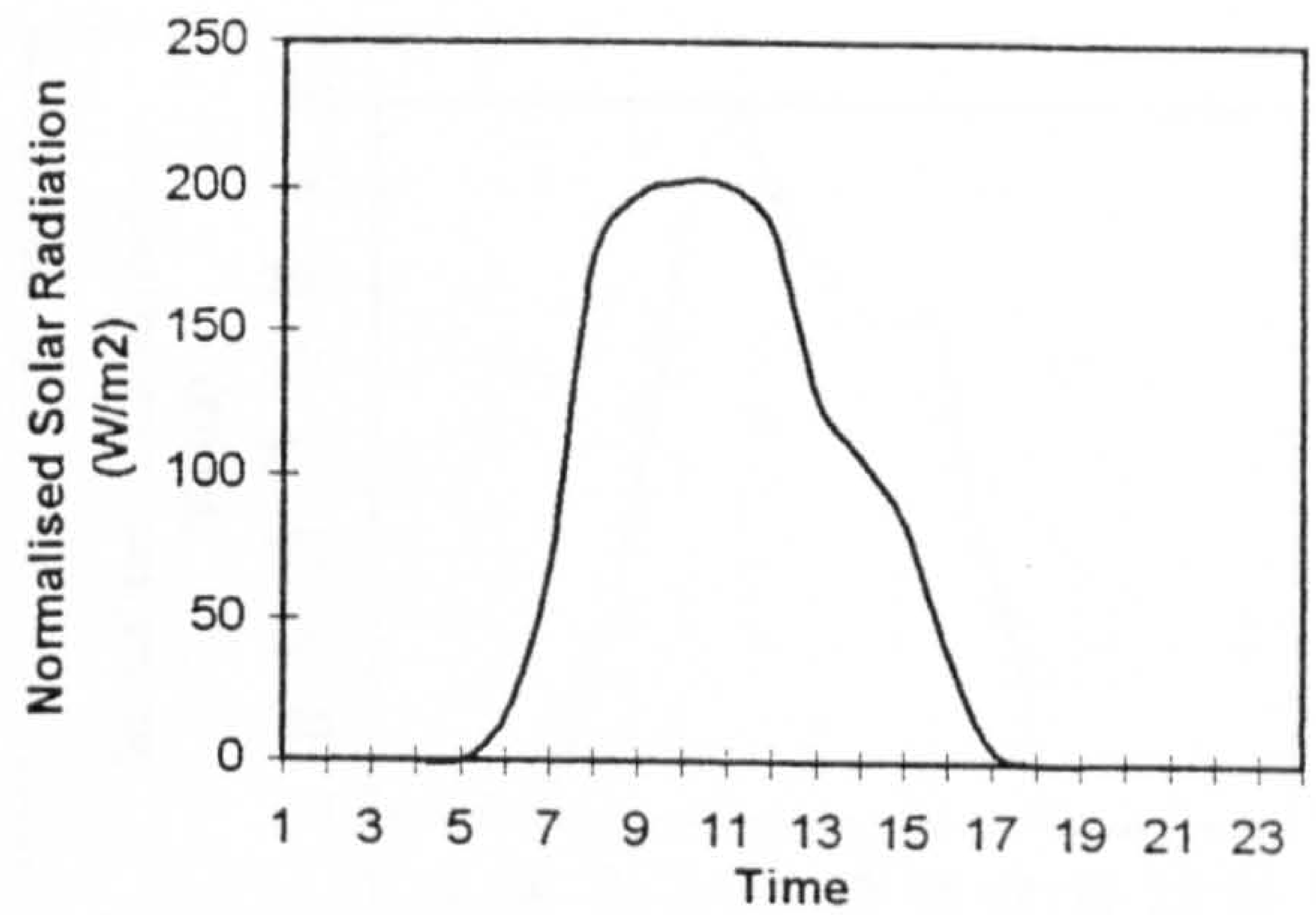

Figure 3.35b:Total Solar Radiation on Walls of Passively Ventilated Building in July

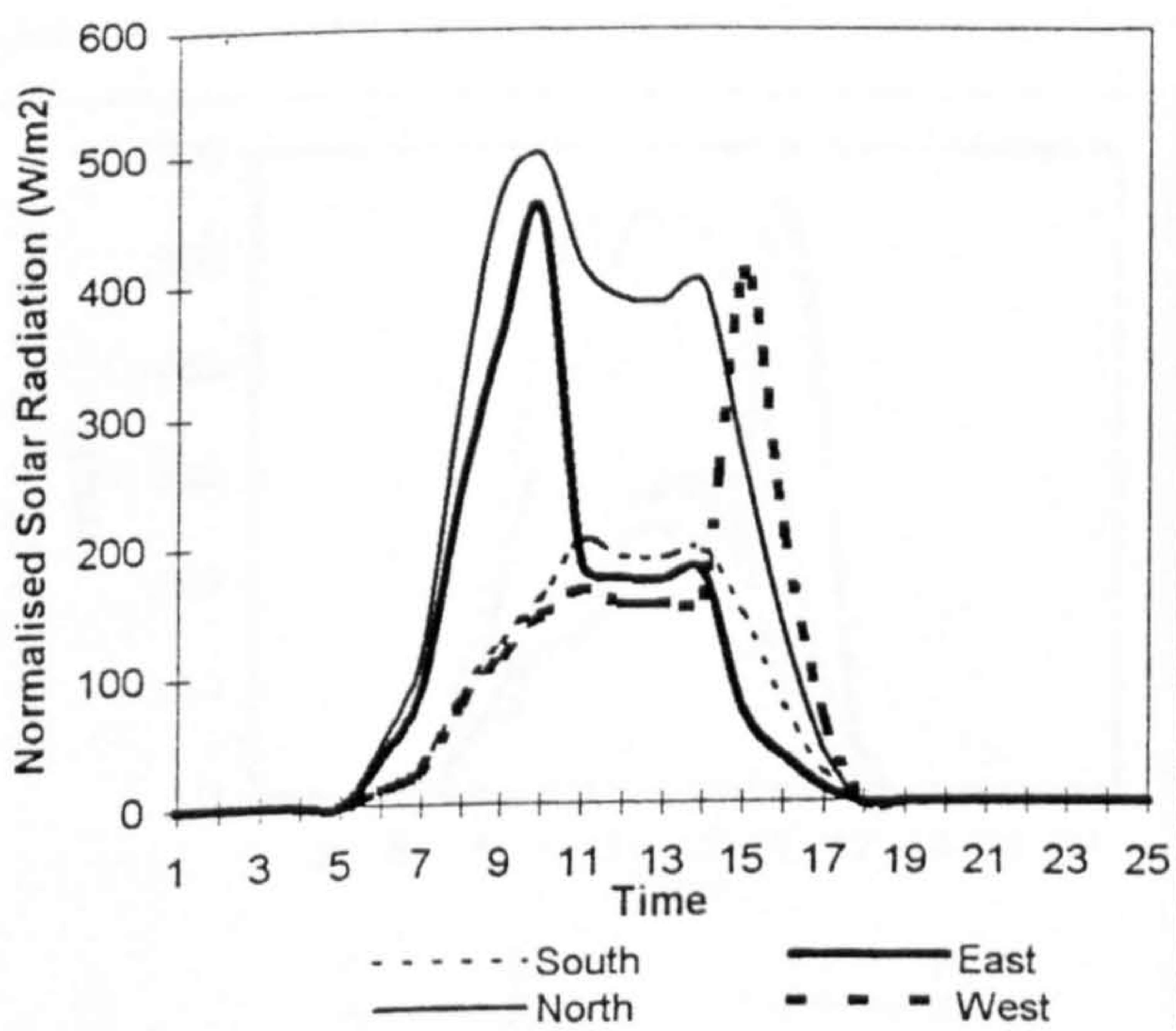

Figure 3.36a: Business Hotel, Solar Radiation on Walls Facing Different Directions in October

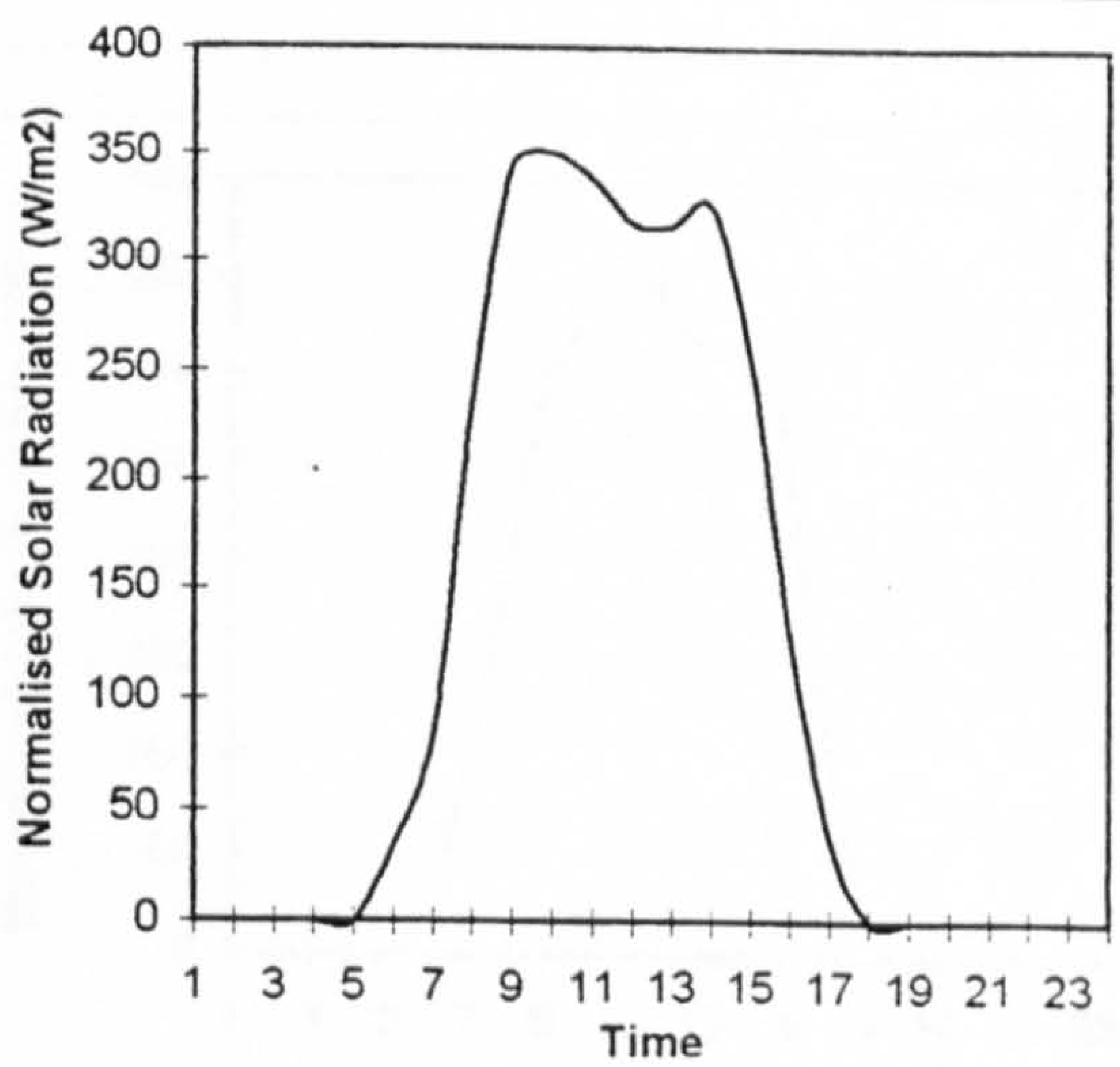

Figure 3.36b: Total Solar Radiation on Walls of Business Hotel in October

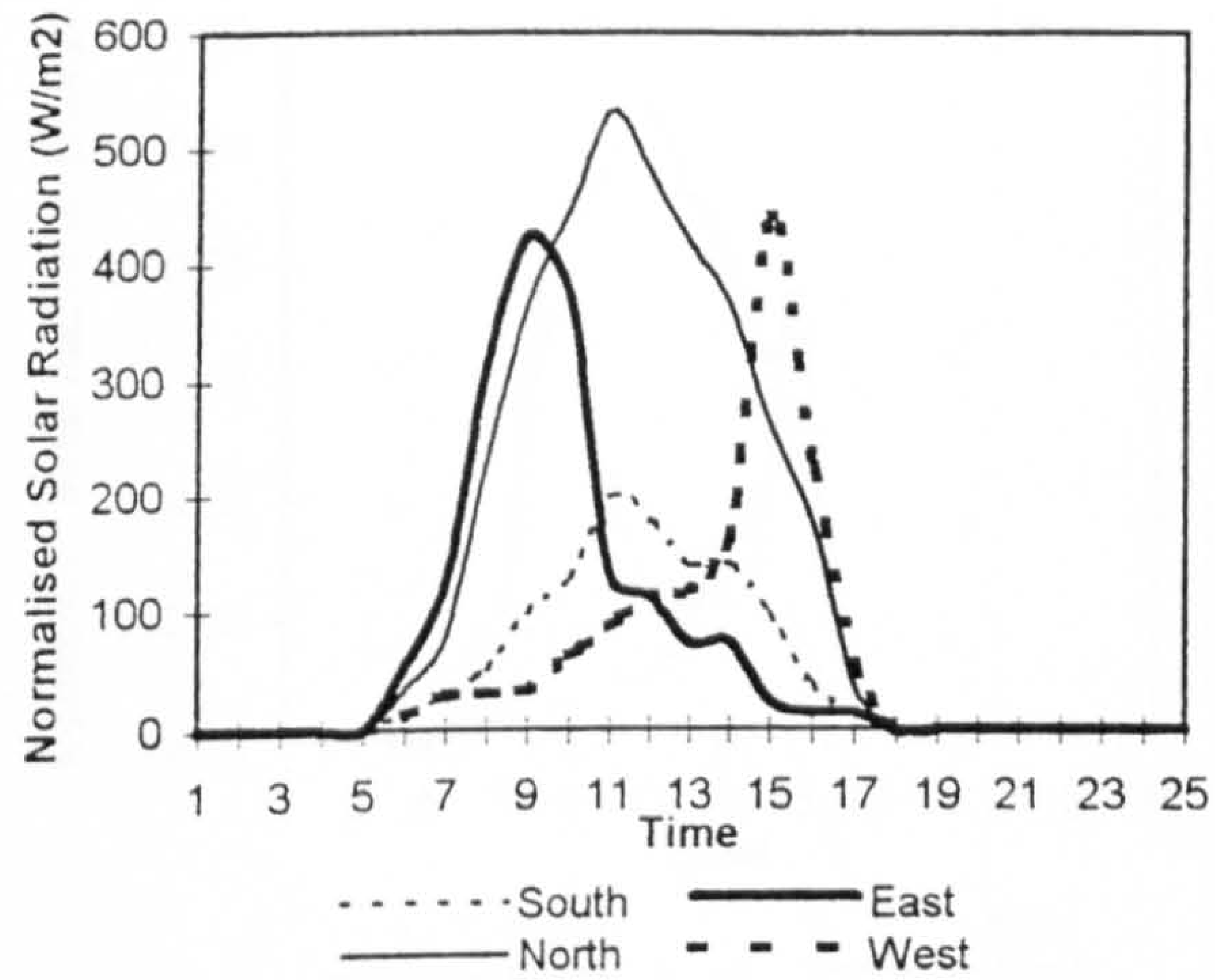

Figure 3.37a: Government Office Building, Solar Radiation on Different Walls in October

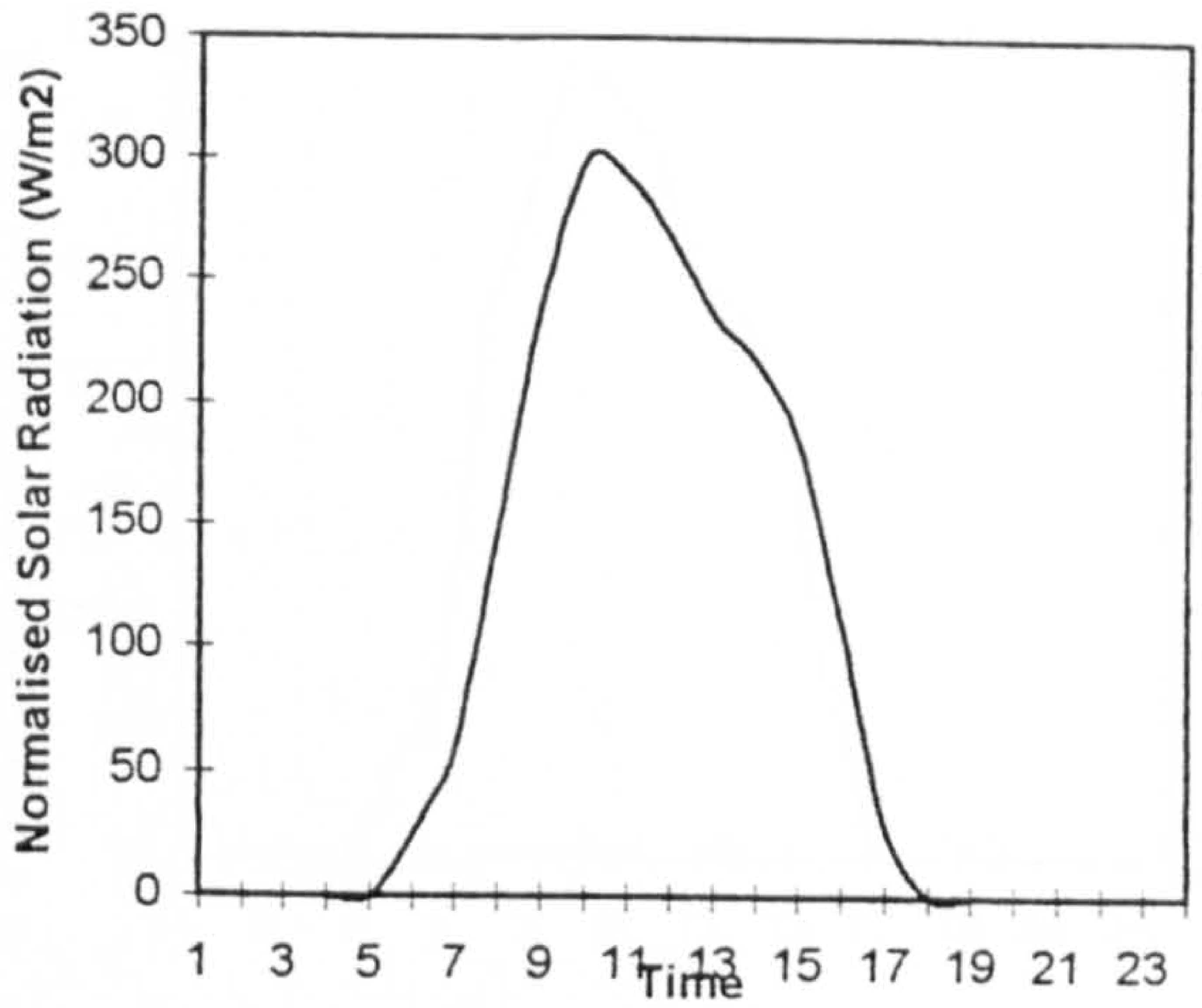

Figure 3.37b: Total Solar Radiation on Walls of Government Office Building in October

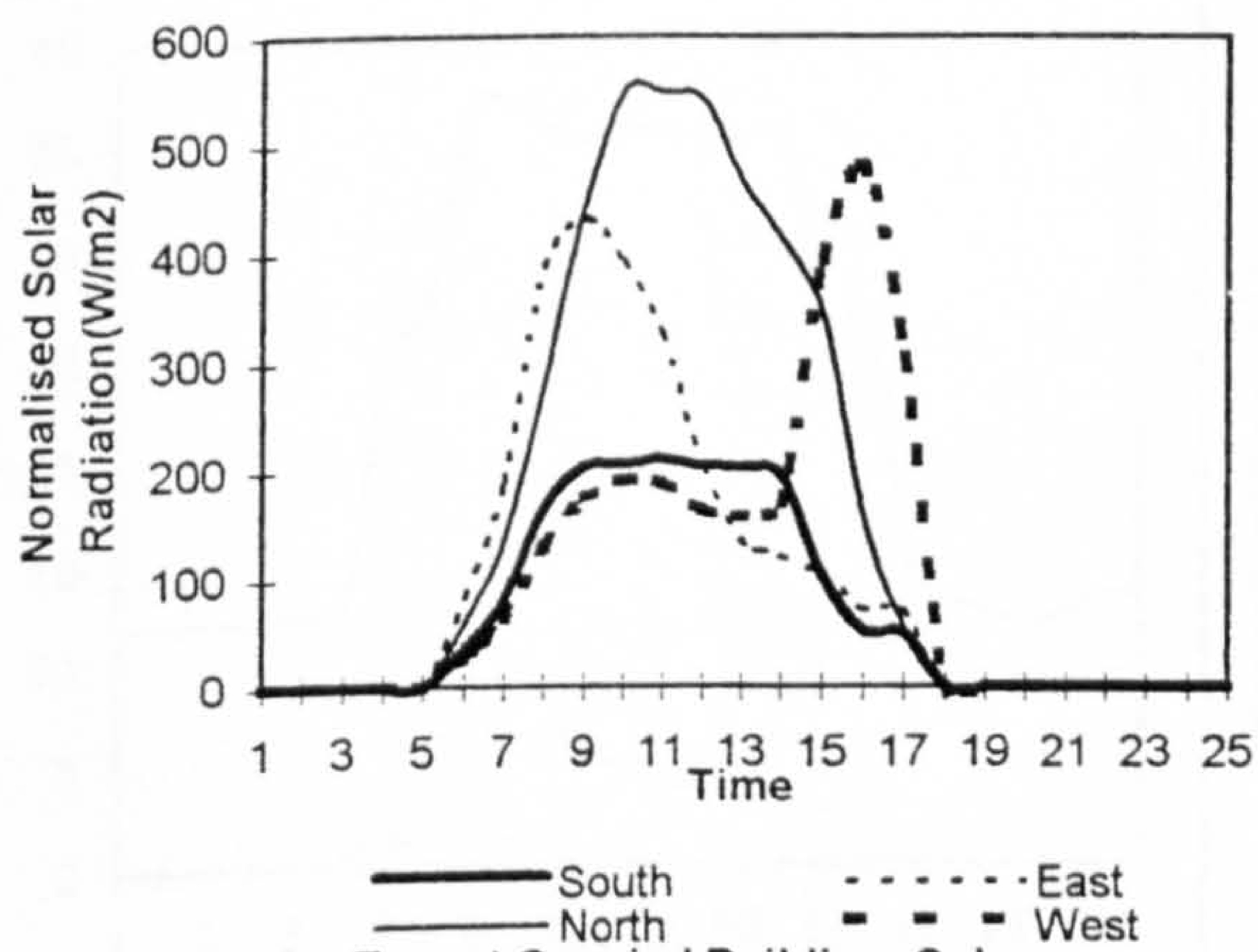

Figure 3.38a: Tenant Ocupied Building, Solar Radiation On Different Walls in October

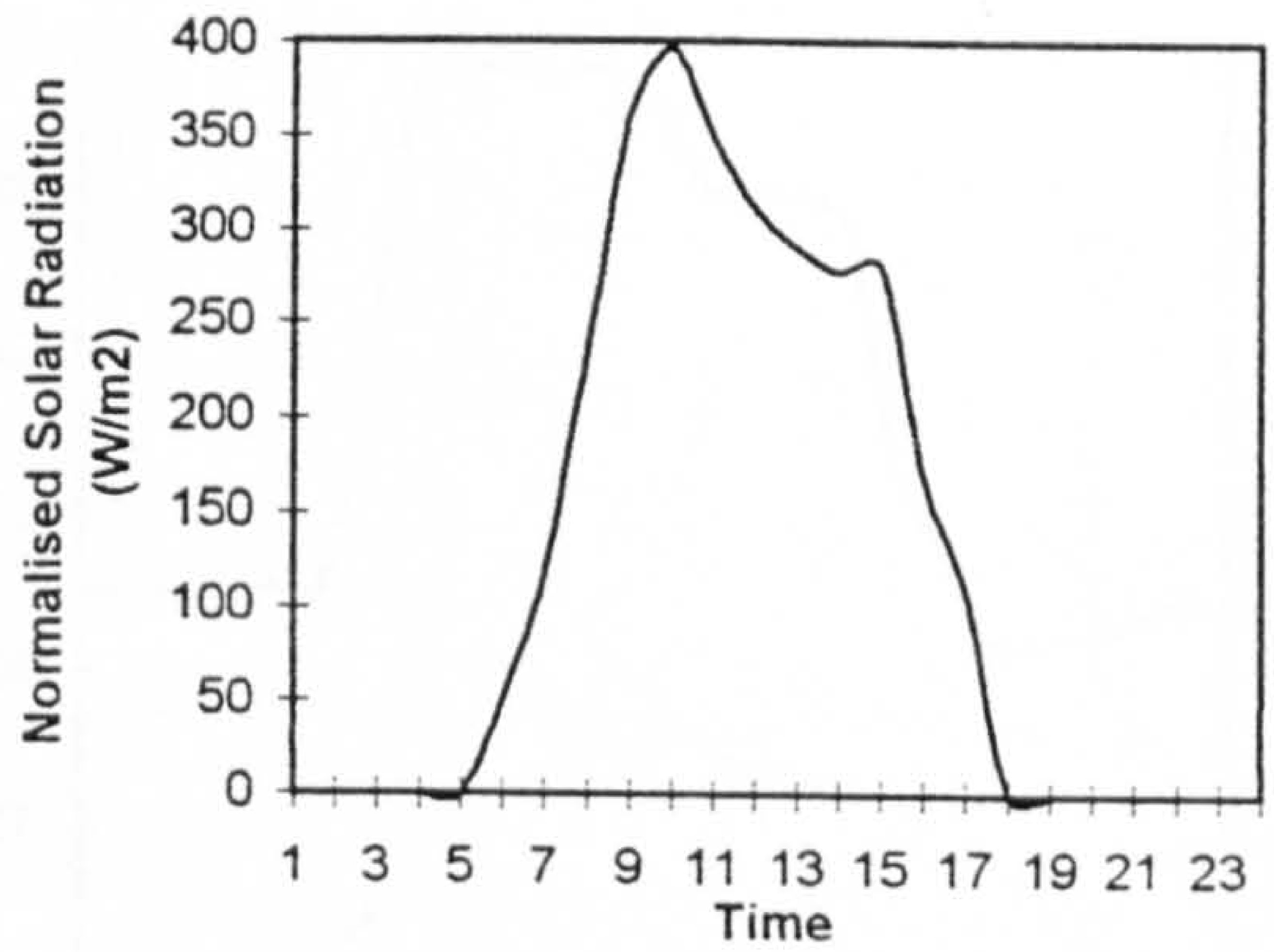

Figure 3.38b: Total Solar Radiation on Walls of Tenant Occupied Building in October

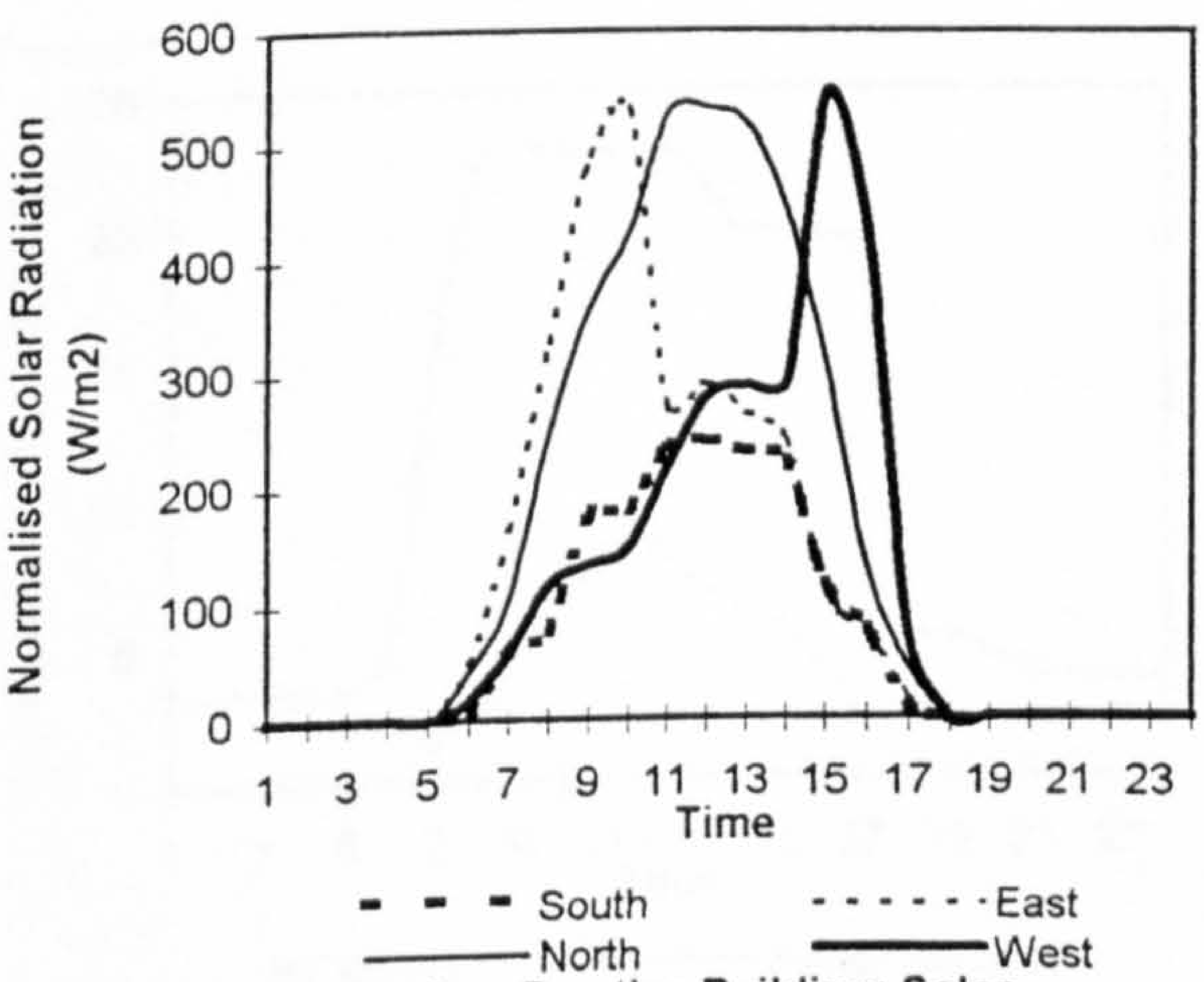

Figure 3.39a: Modern Prestige Building: Solar Radiation on Different Walls in October

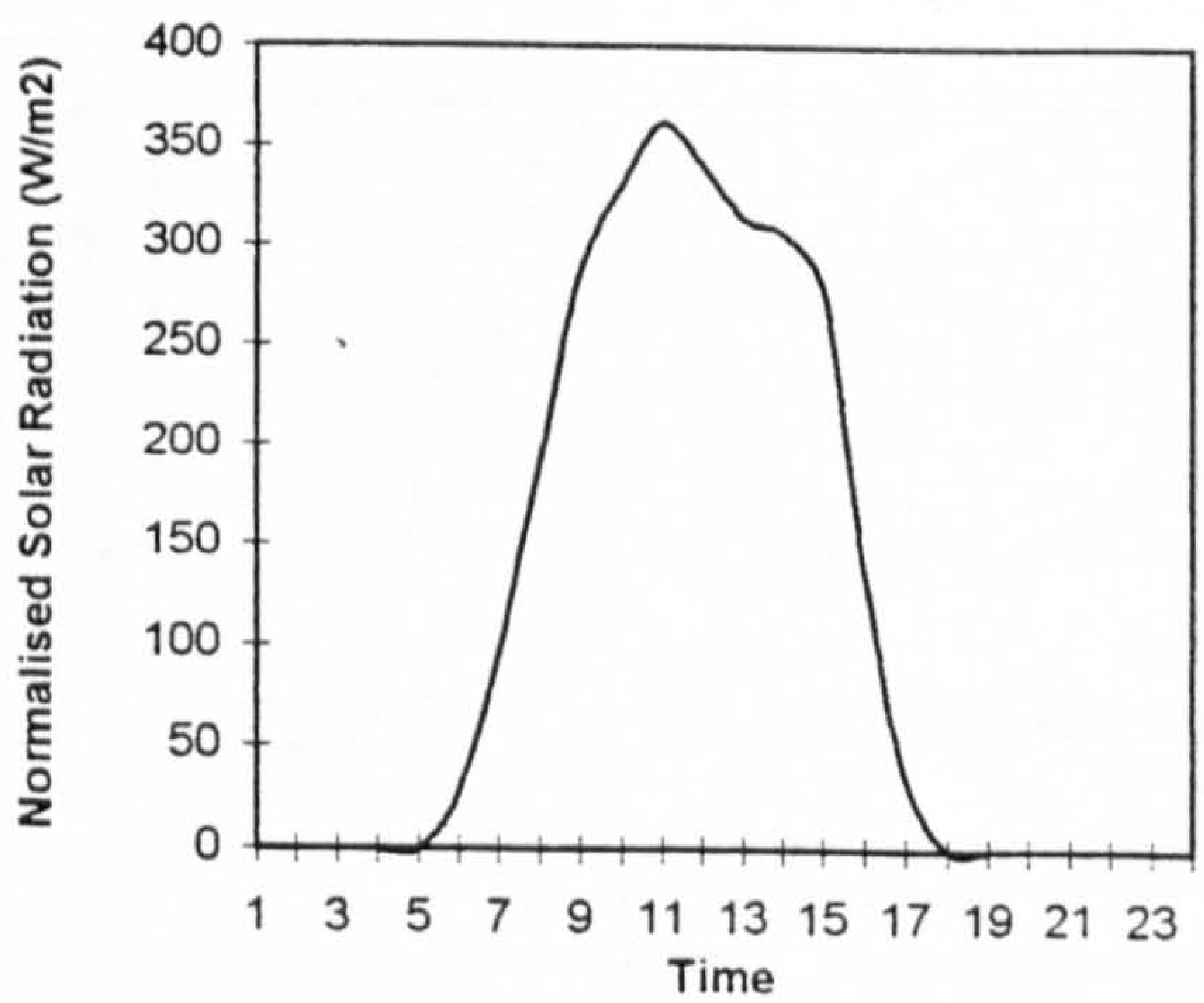

Figure 3.39b: Total Solar Radiation on Walls of Prestige Modern Building in October

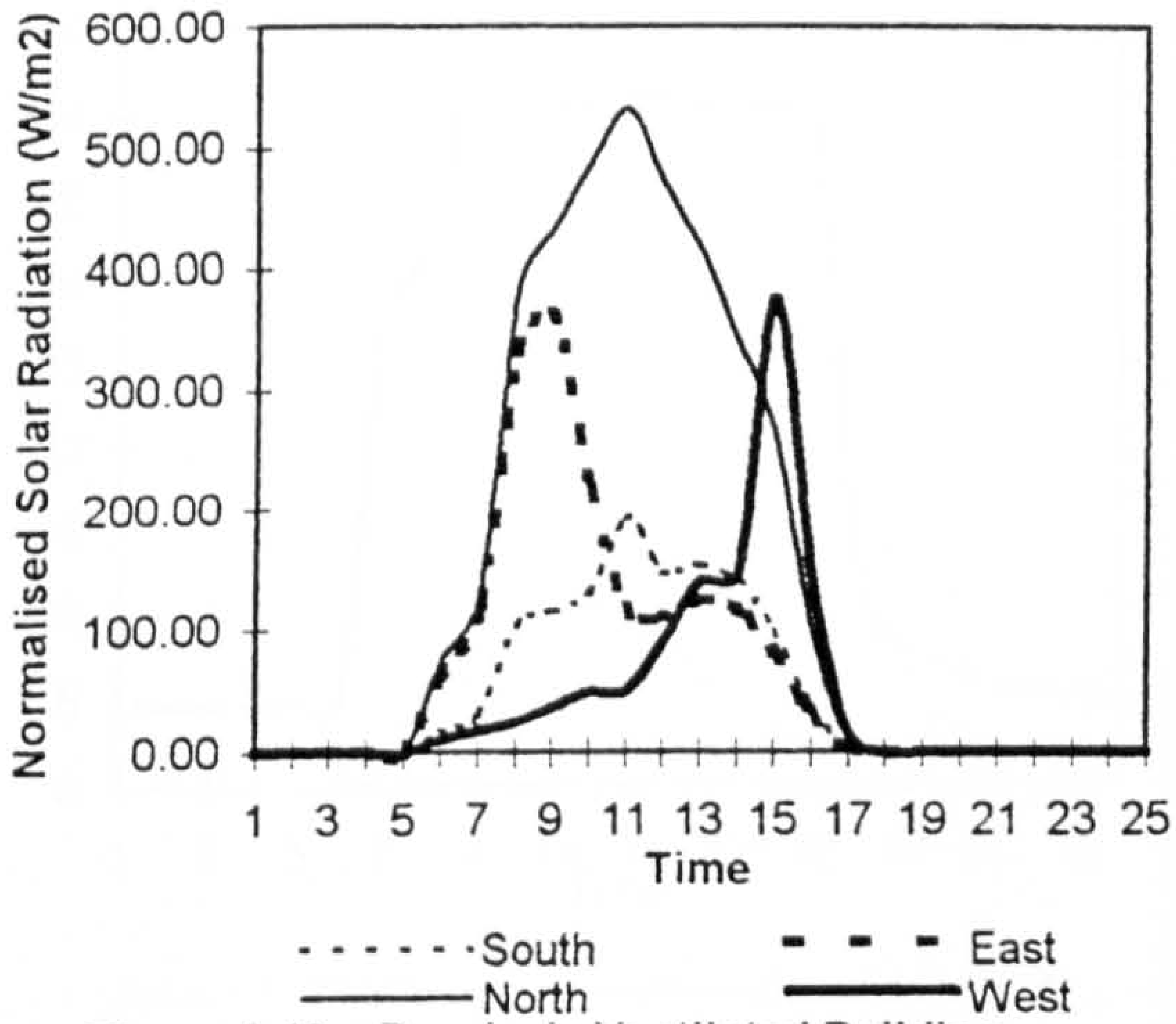

Figure 3.40a: Passively Ventilated Building, Solar Radiation on Walls in October

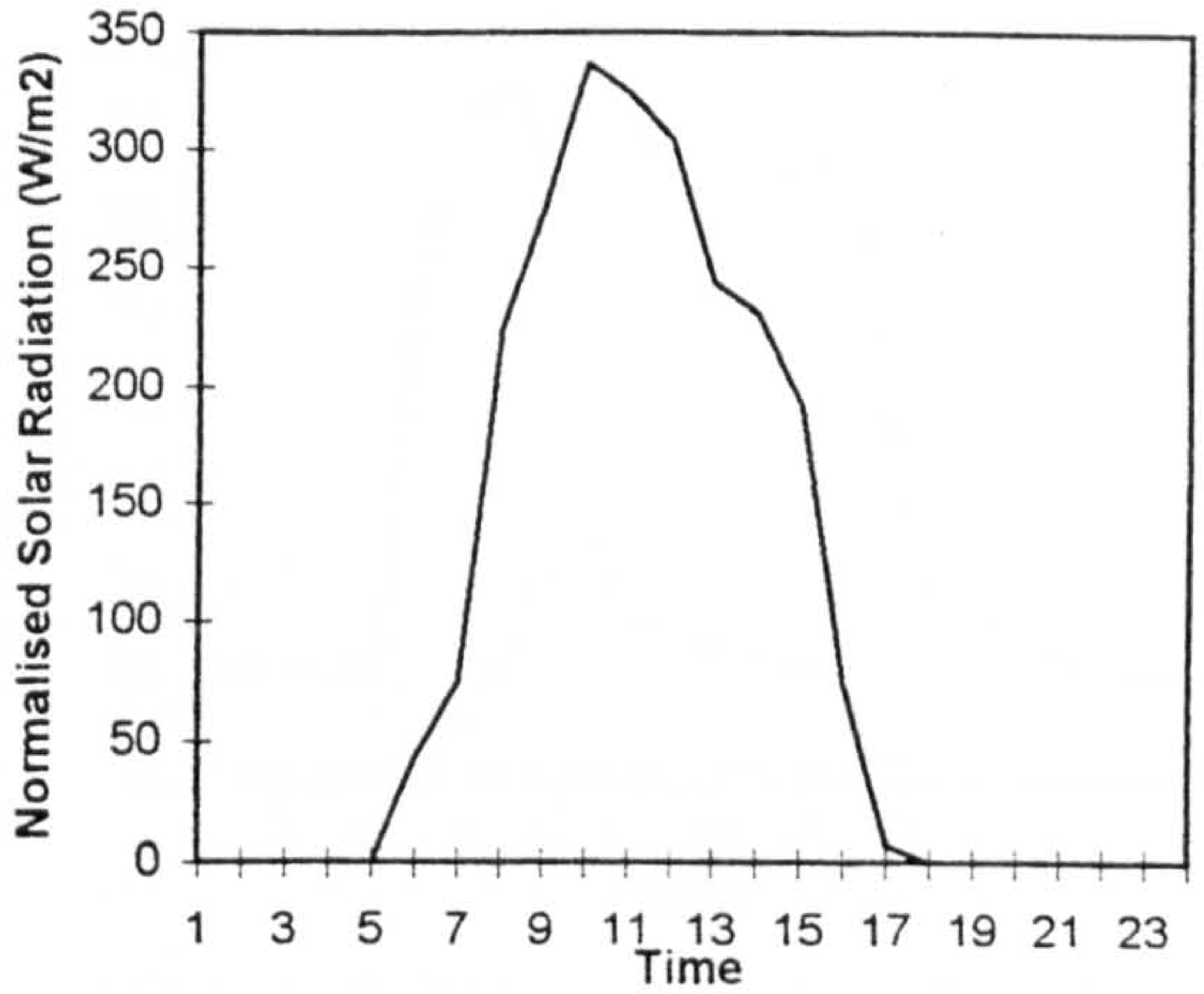

Figure 3.40b: Passively Ventilated Building: Total Solar Radiation on Walls in October

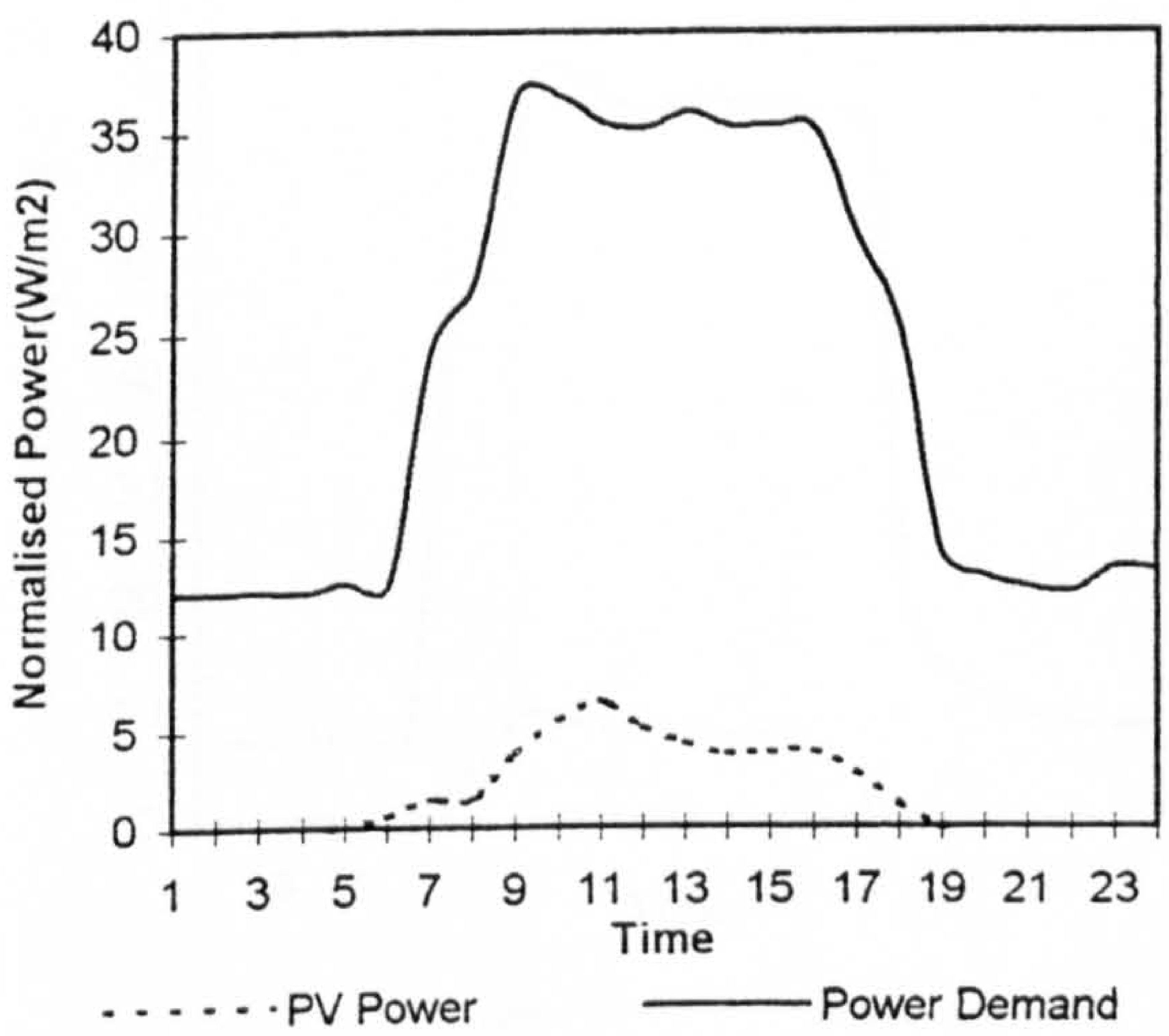

Figure 3.40a: Business Hotel, PV Power and Building Power Demand in July

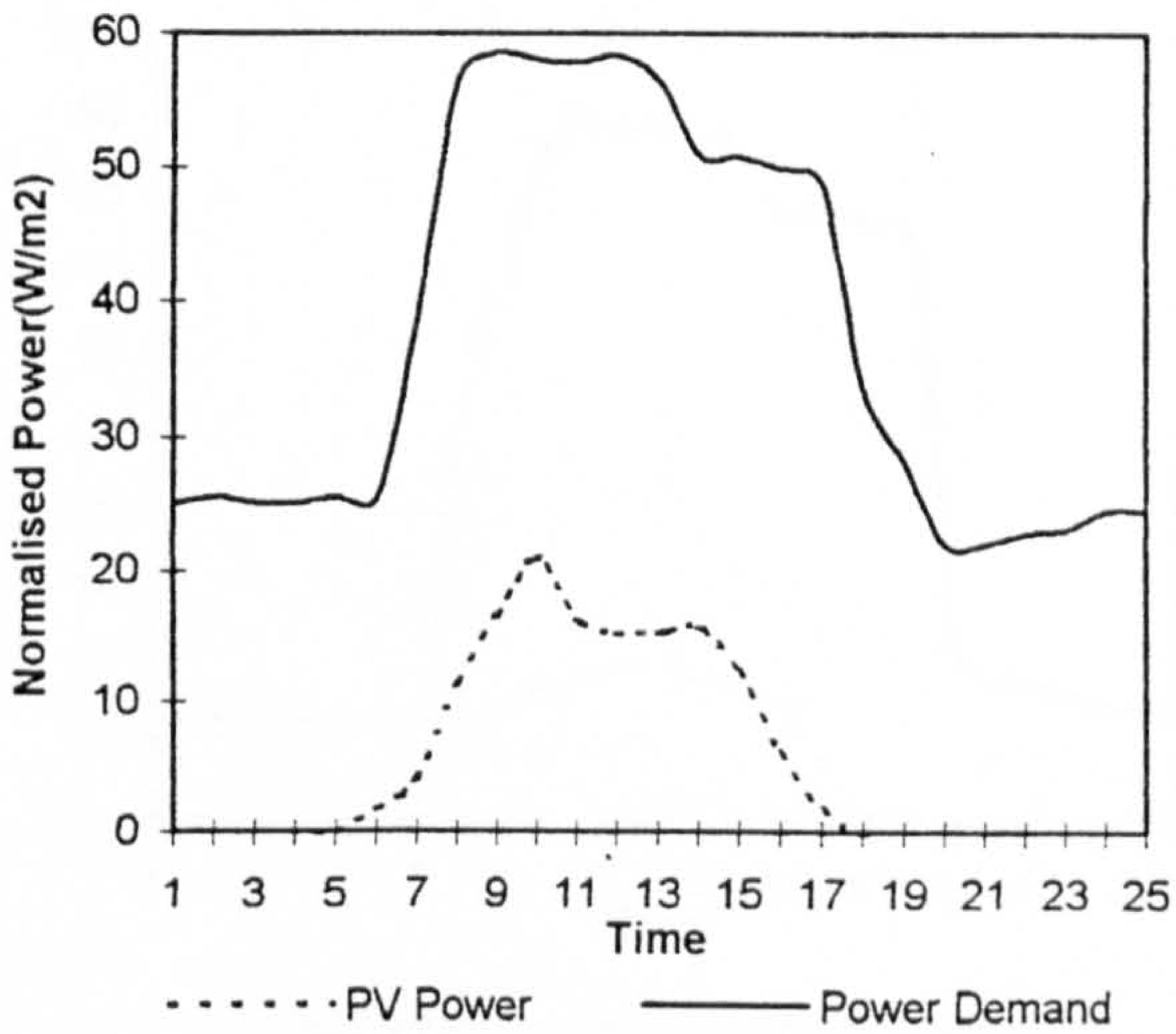

Figure 3.40b: Business Hotel, PV Power and Building Power Demand in October

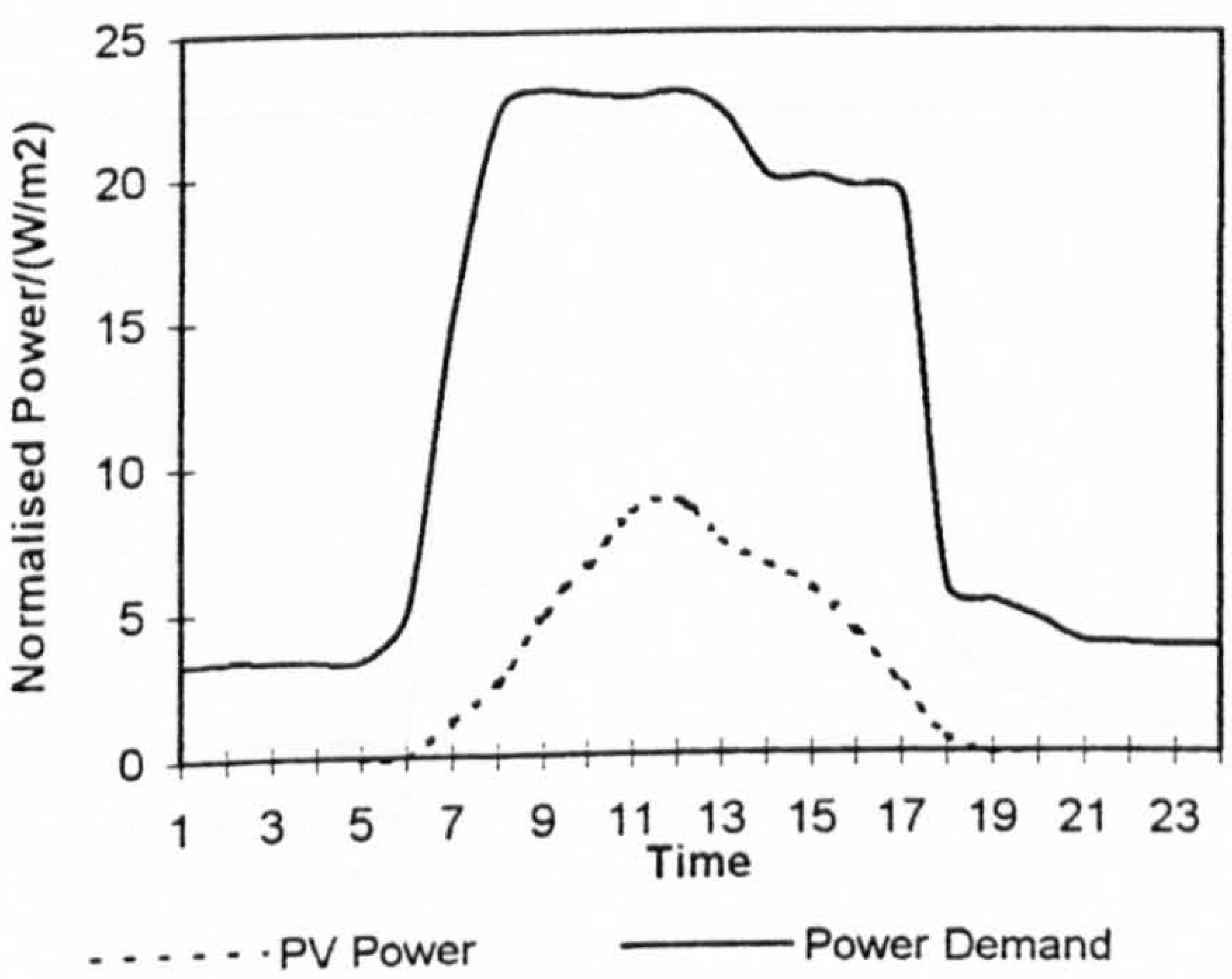

Figure 3.41a: Government Office Building, PV Power and Building Power Demand in July

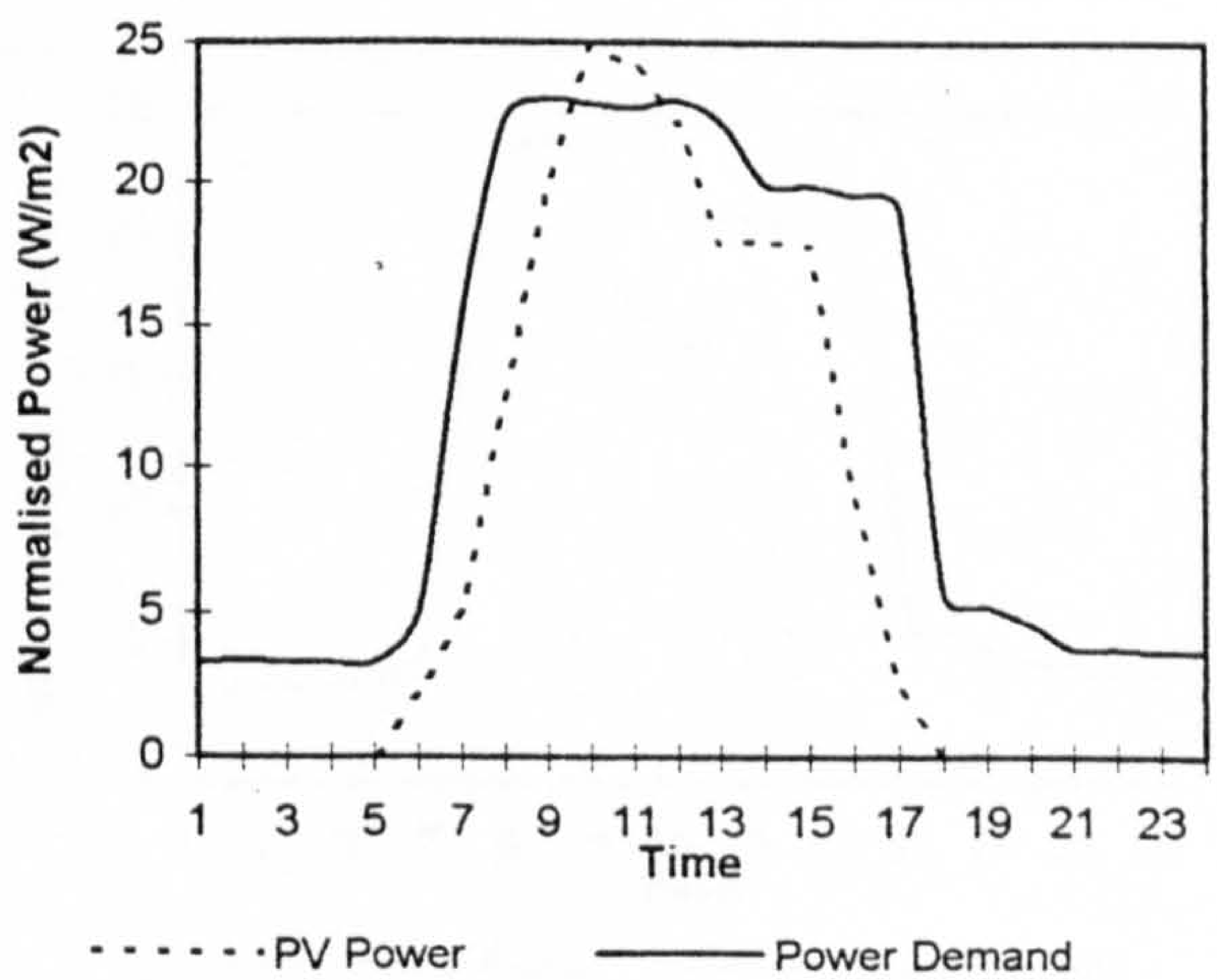

Figure 3.41b: Government Office Building, PV Power and Building Power Demand in October

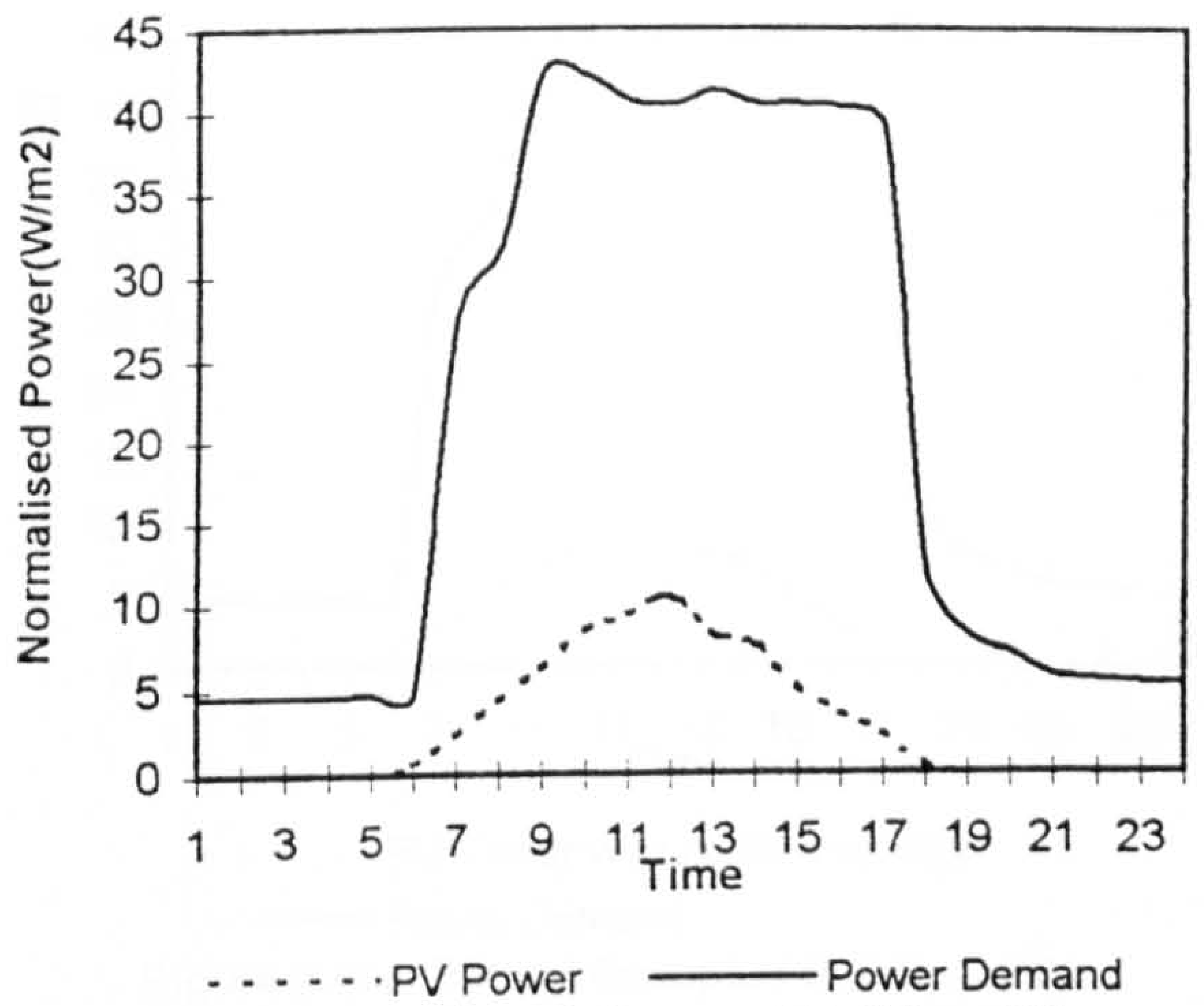

Figure 3.42a: Tenant Occupied Building, PV Power and Building Demand Power in July

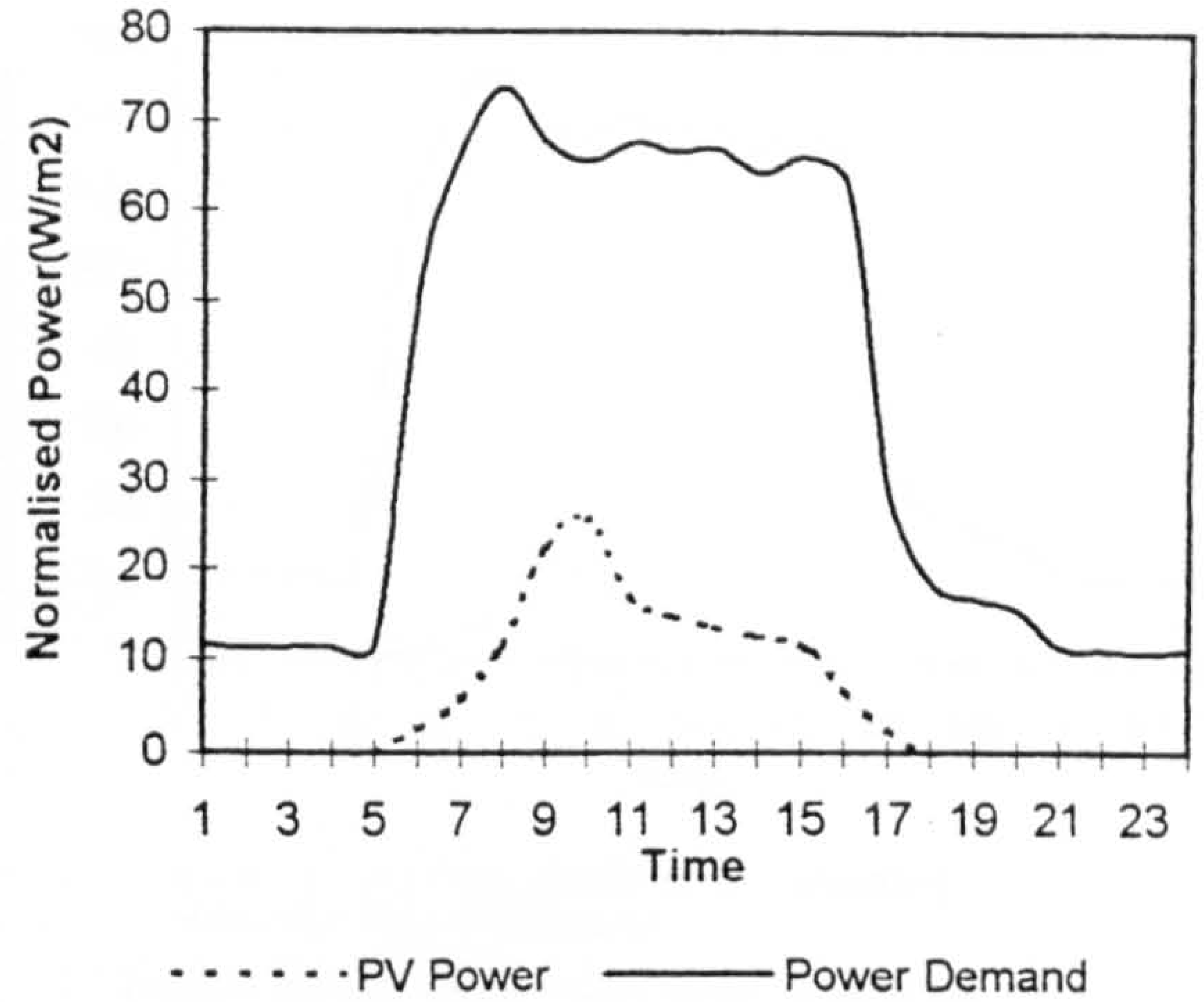

Figure 3.42b: Tenant Occupied Building, PV Power and Building Power Demand in October

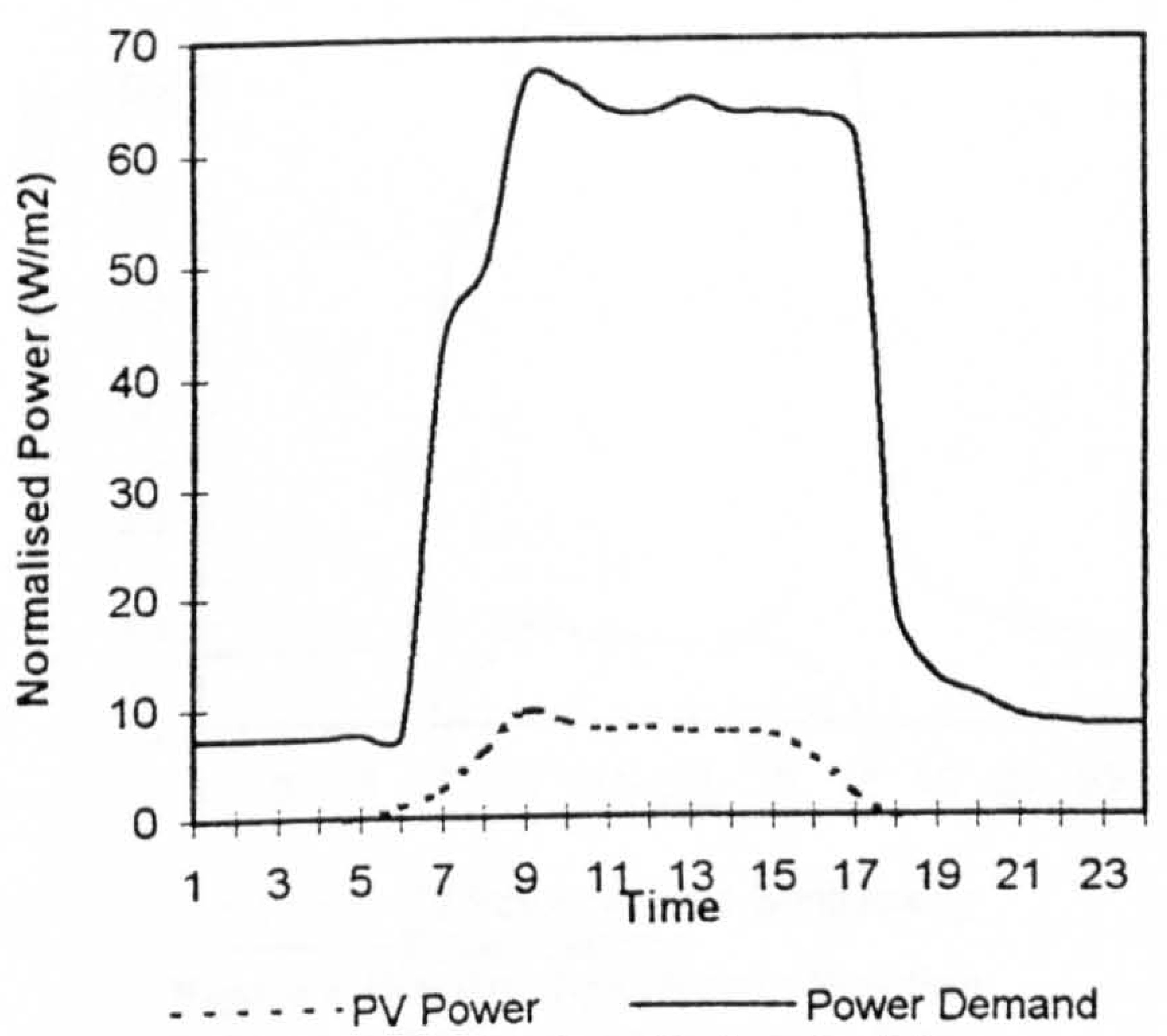

Figure 3.43a: Prestige Modern Building, Estimated PV Power and Building Power Demand in July

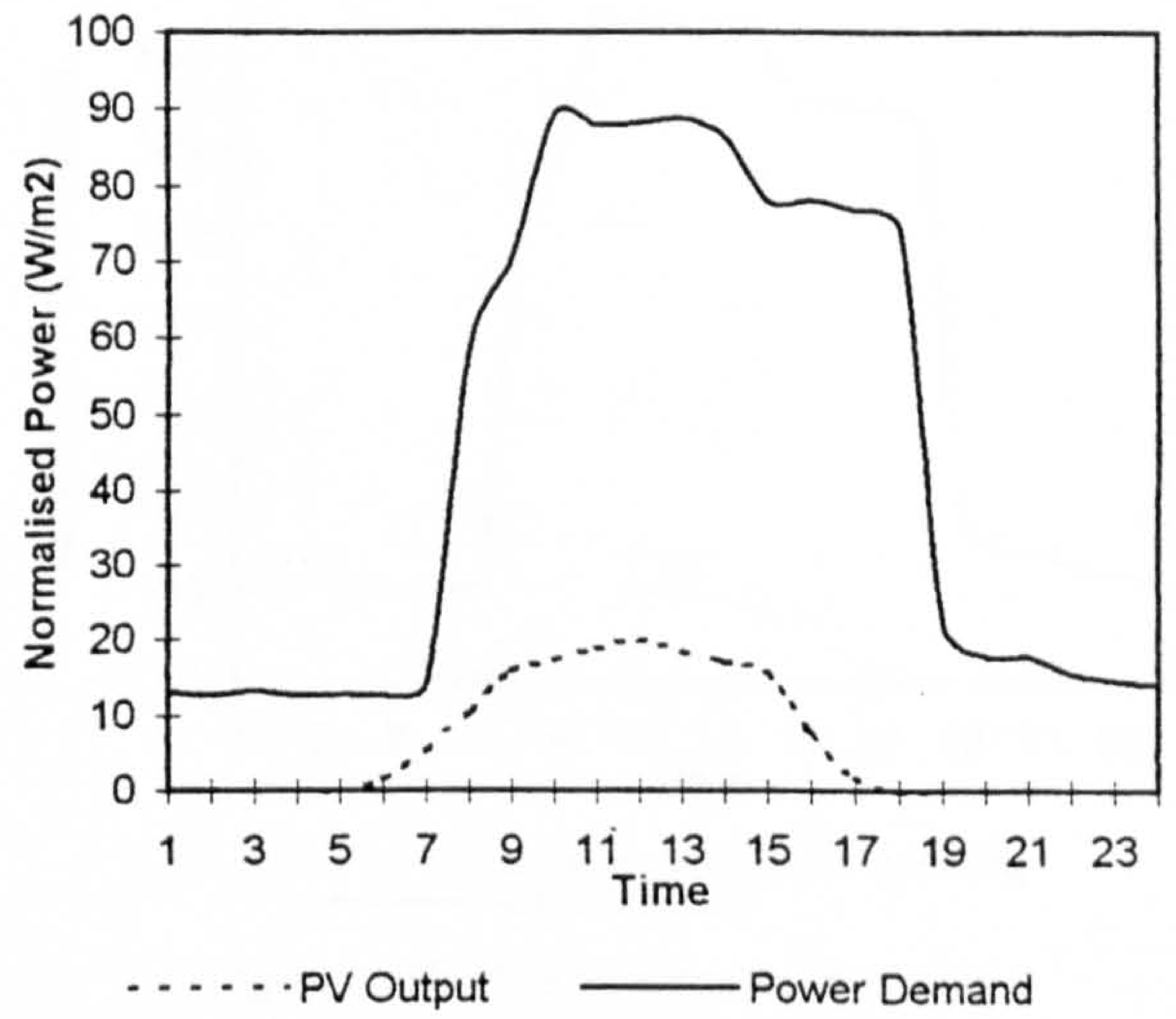

Figure 3.43b: Prestige Modern Building, PV Power and Building Power Demand in October

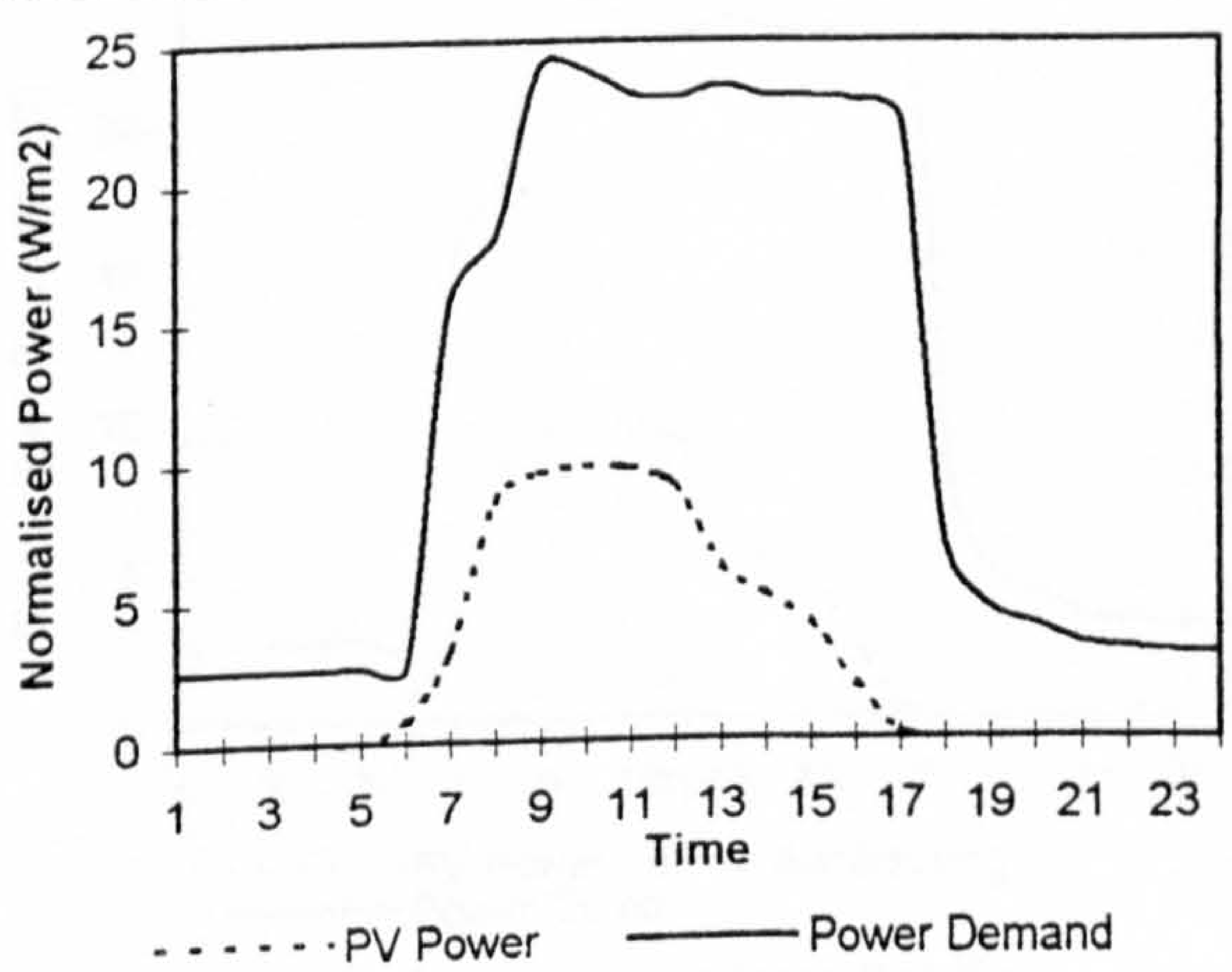

Figure 3.44a: Passively Ventilated Building, PV Power and Building Energy Demand

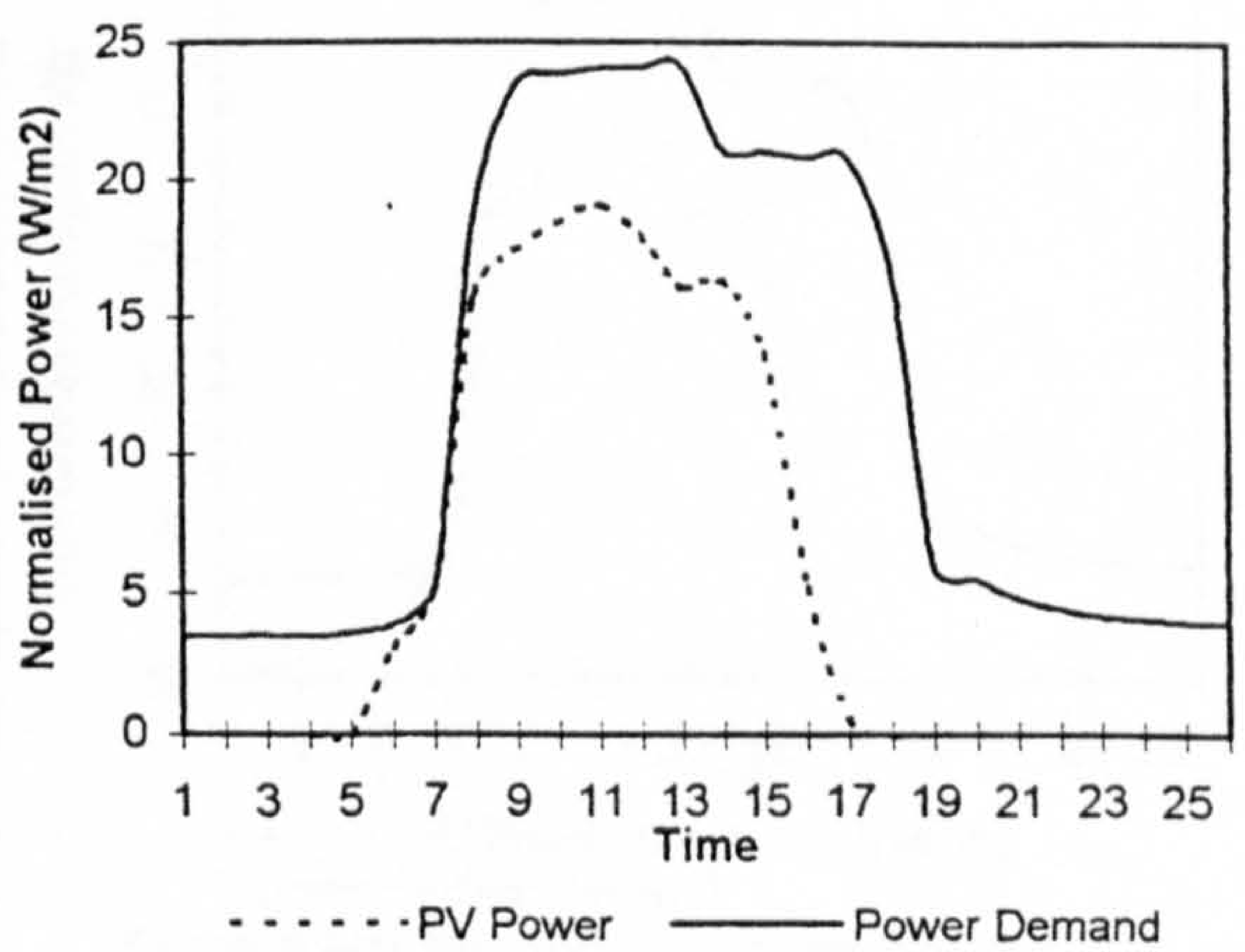

Figure 3.44b: Passively Ventilated Building, PV Power and Building Power Demand in October

3.7 CONCLUSION

Building	Number of Modules on Walls	Potential Installed Capacity	Total Externa l Area	Installed Power per unit area
Business Hotel	4640	394kW$_p$	13427	29.5
Government Office Building	7040	598.4 kW$_p$	17212	35
Executive Commercial Building	3200	360.4 kW$_p$	9530	38
Prestigious Modern Building	2856	217.6kW$_p$	7565	29
Passively Ventilated Building	3712	315.5 kW$_p$	15212	30

Table 3.1: Potential of PV Modules that can be installed on Exemplar Buildings

	Maximum Solar Radiation on Different Walls in July(W/m$^{2)}$				
Building	North	East	South	West	Whole Building
Business Hotel	270	275	160	213	135
Government Office Building	273	267	122	245	180
Tenant Occupied Building	295	251	158	243	220
Prestige Modern Building	268	270	113	230	155
Passively Ventilated Building	275	261	125	249	200

Table 3.2: Maximum Solar Radiation on Different Walls in July

	Maximum Solar Radiation on Different Walls in October (W/m^2)				
Building	North	East	South	West	Whole Building
Business Hotel	500	454	195	410	320
Government Office Building	532	423	260	460	340
Tenant Occupied Building	550	430	200	440	350
Prestige Modern Building	510	530	140	510	342
Passively Ventilated Building	530	428	155	418	341

Table 3.3: Maximum Solar Radiation on Different Walls in October

Building	Max PV Output W/m²	Max Power Demand W/m²	%age	PV Energy Wh/m²	Daily Energy Demand Wh/m²	%age
Business Hotel	7	37	19	54	544	10
Government Office Building	9	23	39	58	281	21
Tenant Occupied Building	10	41	24.5	69	503	14
Prestige Modern Building	10	68	15	73	790	9
Passively Ventilated Building	9	25	36	67	286	23

Table 3.4: PV Output and Power Demands from Different Buildings in July

Building	Max PV Output W/m²	Max Power Demand W/m²	%age	PV Energy Wh/m²	Daily Energy Demand Wh/m²	%age
Business Hotel	21	59	34	137	938	15
Government Office Building	25	23	108	175	281	63
Tenant Occupied Building	26	139	21	145	1864	8
Prestige Modern Building	20	149	14	150	1797	8
Passively Ventilated Building	19	25	76	149	302	49

Table 3.5: PV Output and Power Demands from Different Buildings in October

The Business Hotel building has a curved shape. This affects the solar radiation incident on its north wall because it has both east and west facing portions. Consequently, in Figure 3.31a and Figure 3.36a the graph of north wall has 2 peaks, one in the morning and the other in the afternoon. In July, the solar energy incident on the east facing walls in the morning is higher than that incident on the west facing wall in the afternoon. This is shown by the reflection of the two peaks in the graph of the total solar energy incident on the whole building in Figure 3.31b, where the morning peak is 135W/m² and the afternoon peak is 83W/m². In October, there is a small difference between the peak incident solar radiation on the east facing walls in the morning and that incident on the west facing walls in the afternoon. There is therefore a small difference in the peaks of the graph of the total radiation incident on the whole building as shown in Figure 3.3.6b.The Government office building and the Passively Ventilated Building has a high wall length to width ratios of 4:1 and 3:1 respectively. A larger portion of the incident solar radiation on the whole building is from the north facing walls, that is, 60% for the Government Building and 51% for the Passively Ventilated Building. The graphs of the total solar energy incident on the building therefore follow the shape of the solar energy incident on the north walls of the buildings as shown in Figures 3.32, 3.35, 3.37, and 3.40. The Tenant Occupied Building also has a rectangular plan like the Government Building and the Passively Ventilated Building. However, its length to width ratio is only 1.5: 1. Therefore, the morning peak due to the solar energy incident on the east walls, and the afternoon peak due to the incident solar energy on the west face predominate the graphs of the total building solar radiation. This gives it a near double peak which is more pronounced in October than in July as shown in Figure 3.33, and Figure 3.38. The Prestige Modern Building has an octagonal plan, with sides of the same area. It therefore has a solar radiation graph similar to the Tenant Occupied Building as shown in Figure 3.34 and Figure 3.39. The Business Hotel has the least total solar radiation received per unit external area with a 320W/m^2 peak in October, and 135W/m^2 in July. The Tenant Occupied Building has the highest solar radiation in both July and October with peaks of 220 W/m^2 and 350m^2 respectively.

Tables 3.4 and 3.5 shows that the buildings which do not have air-conditioning plants in them, that is, the Passively Ventilated Building and the Government Building produces PV power which contributes the highest proportion of their power demand. They contribute 21% and 23% of the daily building energy in July respectively, and 49% and 63% in October respectively. The PV modules on the Business Hotel, the Tenant Occupied Building and the Prestige Modern Building contribute10%, 14% and 9% in July to the building power demand. This is 15, 8% and 8% in October, because though the solar energy increases, the building power demand also increases with the increase in air-conditioning power required.

However, the Passively Ventilated Building has the lowest PV power output per unit external area of 19 W/m^2, because the 4 stairways on the each of the north and south walls reduces the area on which the modules can be installed. More PV output can be produced on the Passively Ventilated and Government Building, if some modules are installed on the glazed roof of the atrium of the Passively Ventilated building and on the roof of the Government Building. This would improve the installed capacity from 30W/m^2 to 56W/m^2 and 35W/m^2 to 44W/m^2, giving building peak PV powers of 35W/m^2 and 29W/m^2. The energy demand contribution would also be improved to 87% and 83% respectively.

The installed capacity on the other 3 buildings is 29.5 W/m^2, 38 W/m^2 and 29W/m^2. The peak PV power produced is 21 W/m^2, 26 W/m^2 and 20 W/m^2. The PV power produced on these buildings can be improved through suntracking. This would also improve the contribution of PV power to building power demand. If applied to the non-air conditioned building the PV power can even power the whole building.

Solar radiation incident on the north, east and west walls produce heat gains in buildings which cause discomfort in them. Installing PV modules as sunscreens on such walls could also help in shading the direct solar radiation. In the air-conditioned buildings this would reduce the cooling load on the air-conditioning plant, and hence the electricity required to power the plant. The contribution of PV on such buildings can be significant if compared with the power required by the air-conditioning plant. This therefore requires simulation of the air-conditioning plants as shown in Chapter 4.

The buildings considered here have the relevant features for building integrated photovoltaics However, the introduction of building integrated PV can be improved by considering it as part of an integrated energy model so that it can effectively become part of the building structure which produces power and gives sunshading. The effectiveness of this can be verified by using modular simulation software, incorporating PV as shading components and as a power source, as well as the air-conditioning system as shown in Chapter 5. It would also assist in the financing of installing the PV modules on the buildings, if the savings on electricity cost due to a reduced cooling load, and the reduced cost of an air-conditioning plant could be considered as part of the capital cost of PV modules, as shown in Chapter 6.

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Chapter 4

Commercial Building Energy in Zimbabwe

4.1 Building Energy Loads

The effectiveness of photovoltaics as an energy source has been found to increase if both supply-side energy management and demand-side energy management are considered simultaneously[1]. Traditionally, the power supply of commercial buildings has been designed to meet the maximum demand of the expected loads, with no effort put into reducing the energy load likely to be used. Therefore the total power demand of most existing commercial buildings is likely to be too large for a local power supply, especially one of a variable nature as photovoltaics.

Thus, if photovoltaic systems are to be efficiently applied on commercial buildings, then a firm knowledge of the loads in the building and identification of those likely to be supplied with a specific power source is required. The most likely candidates are those loads on which various control algorithms can be applied to meet certain operating requirements. In a typical commercial building the most significant energy consuming loads include lighting, the air conditioning system, control gear for lifts and electronic equipment such as photocopiers, computers and communication systems. Most of these loads have constant operating schedules. However, the schedules of the air-conditioning load is dependent on the effect of the external weather conditions on the building, and on the response of the occupants to the environmental conditions established by the air-conditioning system.

In the case of the benchmark city the air-conditioning loads have been chosen as the load for which demand-side energy management can be applied in order to facilitate the integration of photovoltaic systems because of their traditional role as sacrificial loads in the event of load shedding. Air-conditioning loads especially cooling loads change cyclically over the 24 hour period of the day[2]. Their cyclic changes are not in phase, and they must be analysed carefully to establish the energy load of the zones in a building on both a short time and a long time period.

4.2 Methods of Environmental Control

The degree of sophistication of an environmental control system depends heavily on the internal heat gains and type of air conditioning which is to be achieved. The options range from having simply openable windows to full air-conditioning systems, and includes options such as using natural forces to create passive cooling systems.

4.2.1.Ventilation

4.2.1a Natural Ventilation

Natural ventilation relies entirely on the natural forces of wind convection(stack effect) and diffusion to move air through a space. For natural ventilation to work effectively there should be as little obstruction as possible between the space being ventilated and the place from where the air is being drawn. If air is taken directly from outside the building it is not possible to provide filtration or extensive cooling and the air entering will be at the same temperature and humidity as the outside air. It will also carry the same dust load. Internal temperatures and humidity will be higher than outside due to internal loads. Noise from outside can also enter the space with little reduction. Although it has the advantage of simplicity and requires no maintenance. It is difficult to provide close control of conditions in a room using simple natural ventilation, and it is also difficult to be certain that pressurisation regimes will be maintained, due to the nature of the forces involved. However, some of these problems can be overcome by drawing air through ducts below the ground to obtain cooling and dust reduction of the air .

4.2.1b. Mechanical Ventilation

This makes use of mechanical means (fans) to ensure that set ventilation rates are achieved. It also allows air entering a space to be pretreated as resistance to air-flow is no longer a problem. Its main advantages are that it allows the quantity of air entering a space to be fixed with some certainty while also giving the option of pretreatment of the air(in the form of cooling, heating and filtration). It also allows the pressurisation regimes to be designed with a high degree of certainty. The disadvantages centres around increased capital and running costs compared with natural ventilation. Without pre-

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Recent information available suggests that capital costs for passive cooling systems are slightly lower than for a conventional air-conditioning system[3]. This takes into account the structural costs which are approximately 60% higher due to the increased weight/complexity of the structure while the cooling plant costs are greatly reduced. Running and maintenance costs will be much lower.

4.2.3 Mechanical Air-conditioning

Air conditioning can be used to achieve virtually any conditions required in a given space by means of mechanical ventilation, cooling, heating, humidity control and filtration. It maintains the temperature of a space at a constant level by establishing a balance between the load generated in the space and the supply air delivered to meet the load. The two common methods of delivering the supply air include keeping the temperature of the air constant and varying the quantity of the air or keeping the quantity of the air constant and varying its temperature. The running and capital cost however increase as the conditions and allowable variation become onerous. Air-conditioning can also be combined with passive cooling systems making use of thermal storage to reduce the peak cooling requirements and therefore the plant capital cost as well as the running costs[4]. The advantage of mechanical air conditioning is that it is possible to specify and achieve tight temperature and humidity limits within a space, as well as controlling noise, dust levels and any required pressure regimes.

Optimum design of air-conditioning systems involves building as much inherent thermal control as economically possible into the basic structure. This control may include thermal massing, insulation, glazing and shading devices. The shape, orientation and air-conditioning capacity of the building may also be used to the best advantage. The exterior load may vary from 30 to 60% of the total air-conditioning load when the fenestration area ranges from 25 to 75% of the floor area[5]. Therefore, it may be desirable to minimise the perimeter area since a rectangular building may require more refrigeration than a square building of the same area. Office buildings usually consist of perimeter zones and interior zones. Perimeter zones usually extend 4 to 6 metres inwards from the outer wall and usually have large window areas. They may be subdivided extensively and also tend to have variable cooling loads in summer because of the variable sun position and the weather. At some times of the year there may also be different cooling demands from different sides of the building. However, the thermal loads of interior zones are almost wholly derived from lights, office equipment and people. They therefore require an almost constant cooling regime throughout the year, usually provided by a variable volume control[6].

4.2.3a Methods of Air-Conditioning System Operation

Low cost cooling of a building can be achieved by passing fresh air through it or by circulating water that has been cooled in an evaporative cooling tower on the roof, through the chilled water coil in the air handling unit. Direct evaporative cooling from sprayed air within the air handling plant can be used in countries within the tropics like Zimbabwe. Both methods consume electricity in terms of energy for pumps and fans. Savings can be obtained by controlling the power consumption of the refrigeration compressor or the energy supplied to the absorption chiller. Cooling with fresh air use rather than refrigeration means that up to 100% of the room air supply can be cooled by outdoor air. The availability of air depends on

i. time of the year
ii. time of the day
iii. fresh air intake location which has to be a position where cool and uncontaminated air can be found, usually shaded and above the street level. The availability of the shade depends on the orientation of the building and the time of the day. Underground tunnels of air can be used to lower the temperature of the fresh air intake.
iv. space availability so that the building's facade is available for fresh air intake and exhaust louvres are sufficient for the passage of all of the supply air volume flow rate.

An evaporative cooling tower lowers the water temperature circulated through it towards the outdoor wet-bulb air temperature. Water evaporation increases the cooling effect of the outdoor air. When the wet-bulb air temperature is below supply air temperature needed to cool the room, usable free cooling is potentially available.

Restricted plant room locations near the ground level limit the amount of free cooling that is achievable. Extensively louvred plantroom walls at roof or intermediate floor levels can be utilised. The amount of free cooling provided is controlled by varying the proportion of fresh air in the room air supply system. The proportion moves from a minimum up to 100% by the operation of motorised dampers on the fresh air. The minimum fresh-air intake corresponds to the occupancy at peak winter and summer external design conditions. Variable amounts of fresh air are admitted between these extremes. The dampers have a linear characteristic that relates flow to opening. The objective is to minimise the use of cooling energy while maintaining the specified internal air conditions.

Traditionally dual duct, induction or fan-coil systems have been used in office buildings, but variable air volume systems are increasingly being used now[6], although it is still debatable whether it is a better system than constant air volume(CAV) systems.

i. Variable air volume (VAV) Systems

Variable air volume systems are becoming the standard system for office buildings because they are economical and easier to control when applied to rooms with similar air conditioning requirements[7]. They also have the ability to use independent operating schedules between floors occupied by different tenants and this results in low fan power and low energy cost[8]. The AHU provides the lowest air temperature required. Reductions in room cooling load due to variation in the weather or due to the presence of additional heat gains from occupants or electrical equipment, are met by changing the supply-air quantity with terminal variable air volume controllers until the room air temperature is stabilised. The minimum quantity of supply air permitted responds to at least the fresh air needs of the occupants: thus the turn down may be from 100% down to around 20%.

The cooling loads are usually less than their design peak values for most of the year in Harare, and the airflow rate through the buildings can be reduced. When the room air temperature falls, the cool supply air volume is reduced until the desired temperature is reached again. This process is repeated in other VAV controllers at the same time. The characteristic performance of the centrifugal supply air fan in the main air handling unit is to increase its output static pressure as the volume flow rate is reduced. This is contrary to room requirements as a higher duct pressure would tend to overcome the control effect of the VAV unit. The main supply air duct static pressure is sensed and used to reduce the speed of the fan by means of a variable frequency inverter. The fan speed is lowered slowly until the set point of the static pressure controller is established. This is also done with the recirculation air fan. Operating the two fans at less than their maximum speeds greatly reduces the electrical power consumed by them. The air supply flow rate is varied by a throttling valve and a fan.

The conditioned supply air enters the room through a diffuser, which may be a ceiling linear diffuser along the external perimeter. A plenum above the diffuser acts as a header box to distribute the air uniformly along its length. A throttling valve between the plenum and the diffuser controls the airflow rate. A fan-powered terminal box is located in each building module. The fan may be used to deliver a constant volume flow rate into the room and have a variable proportion of cool air from the central plant, modulated by the VAV damper. This ensures that the correct air distribution through the room is maintained. However, a terminal fan is an additional capital cost and maintenance consideration. Varying the supply air flow has a strong influence upon the distribution of air into the room and the movement of air within it. The supply air is diffused into the room along the length of the external wall and is blown across the ceiling and down the glazing.

VAV systems however need to be carefully designed for low load conditions so that adequate air movement and fresh air can be provided without overcooling at the chosen design supply air temperature[9]. Higher supply air temperatures tend to offset the savings on energy due to reduced fan power inherent in the VAV systems[10]. Airflow along a surface adheres to that surface and forms a thick boundary layer. Low air flows created during normal use of a VAV system can lead to discomfort for a variety of reasons[11]. Thus, dumping, whereby occupants may feel cool downdraughts can be experienced if the cooled supply air does not mix sufficiently with the warm entrained air due to low jet speed and greater density of cool air. This can be solved by using narrow slot diffusers or fan-powered units. Stagnation can also be experienced due to reduced airflows which result in reduced air changes of the room. Parts of the room may also be starved of sufficient air circulation and become too warm owing to local heat sources. Dilution of air may result in stuffy indoor environments leading to cases of sick building syndrome. This can be solved by placing the air volume flow control box of the VAV system in a flow void with the supply duct rising to a sill level grille instead of in the false ceiling.

ii. Constant Air Volume (CAV) systems

This is a common system for occupied large single-volume rooms, offices, atria and computer rooms. Recirculation allows retention of the conditioned air that has been expensively produced with only the correct quantity of fresh air being admitted. Free cooling is possible by adjustment of the dampers following schedules of air temperatures. The supply air quantity will be between 4 and 20ach through the room[12]. The amount of fresh air is calculated from the occupancy. It is typically 8l/s per person for offices and up to 25l/s depending on behaviour related ventilation requirements[13]. Such a fresh air admittance is likely to create 1ach to the room air-change rate that is required to flush out potentially stagnant pockets produced by the grilles and diffuser. Thus the fresh air proportion of the ducted air supply will be 25% or less. This system satisfies the conditions for one room and is unsuitable for multiroom buildings that have different simultaneous air temperature requirements[14]. The room can be large but all parts of it are supplied with identical supply air. The volume flow rates to different parts of the room are in proportion to the localised heating or cooling loads, but the same average condition exists throughout the space. This system can be adapted to serve many rooms such as offices by installing additional heater coils(terminal reheaters), at the room end of the ducts. An air-temperature sensor in each room modulates the reheat coil water-flow control valve to maintain the desired room condition. The temperature of the air that leaves the AHU in the plantroom is that for the room requiring the lowest supply air temperature. The other rooms have a few degrees of reheat.

When rooms can be formed into two or four zones that are to be supplied from the same AHU, a multizone plant can be designed to incorporate two or four outlet ducts. Each duct has a reheat coil and a zone air-temperature controller. Zone reheat coils can be in the supply air duct as it enters the zone. Several zones can be connected to a AHU. Each zone has a number of rooms that will be satisfied with one supply air-temperature, such as, a row of one person offices along one facade of the building or a similar row of modules in an open-plan office.

However, CAV does not offer as much energy savings as VAV because it lacks the system diversity of VAV systems due to the need to supply all the zones served by the system with 100% of their peak flow at all times, instead of only under peak cooling conditions as in VAV systems[15]. They are therefore designed to meet the sum of peak zone loads instead of the building peak load as in VAV systems. These systems have however, found wide application because the sensitivity of the VAV system to proper design has left a negative impression on many who have failed to meet its demanding design criteria. There are times when CAV systems have also been preferred after concluding that the cost of VAV boxes, which is dependent on local availability, could not be offset by energy savings in the VAV systems[16]. Indeed, a survey in the benchmark city revealed that the CAV systems where considered more reliable than VAV systems, and most new buildings had CAV systems.

4.3 Case Studies of Commercial Buildings in The Benchmark City

The five exemplars chosen in Chapter 3 were studied in more detail so that further studies of their energy consumption could be carried out. The regimes of typical commercial buildings are generally similar, but that of hotels are different. A commercial building where energy efficiency has been the prime motivation also possesses unique design features. Consequently, the details of the Business hotel and the Passively Ventilated Building are given in more detail here, than the other 3 typical commercial office buildings.

4.3.1 The Business Hotel

4.3.1a. Building Description

This is an arc-shaped 19-storey building with 227 lettable rooms occupying floors 3 to 19. Each of these floors has 18 rooms and occupies a total of 814.6m^2. Its floor plan is shown in Figure 4.1.

The exterior walls of the rooms are of 23cm thick reinforced concrete and have windows with a window to wall ratio of 2:1 covering their length as well as a 15mm masonry cladding. For construction purposes the rooms can be considered paired and each pair of rooms is separated from the next by a 19cm thick brick wall. The rooms within a pair are separated by a 16.5cm concrete block wall. All the inside walls are covered with 20mm plaster. The exterior wall of the corridor is of 11.5 cm concrete block with a window to wall ratio of 0.33.

The first floor has a lobby, function rooms and a bar. The ground floor consists of a reception, foyer, bar, kitchen, shops and bank. Workshops and staff service rooms are located in the basement.

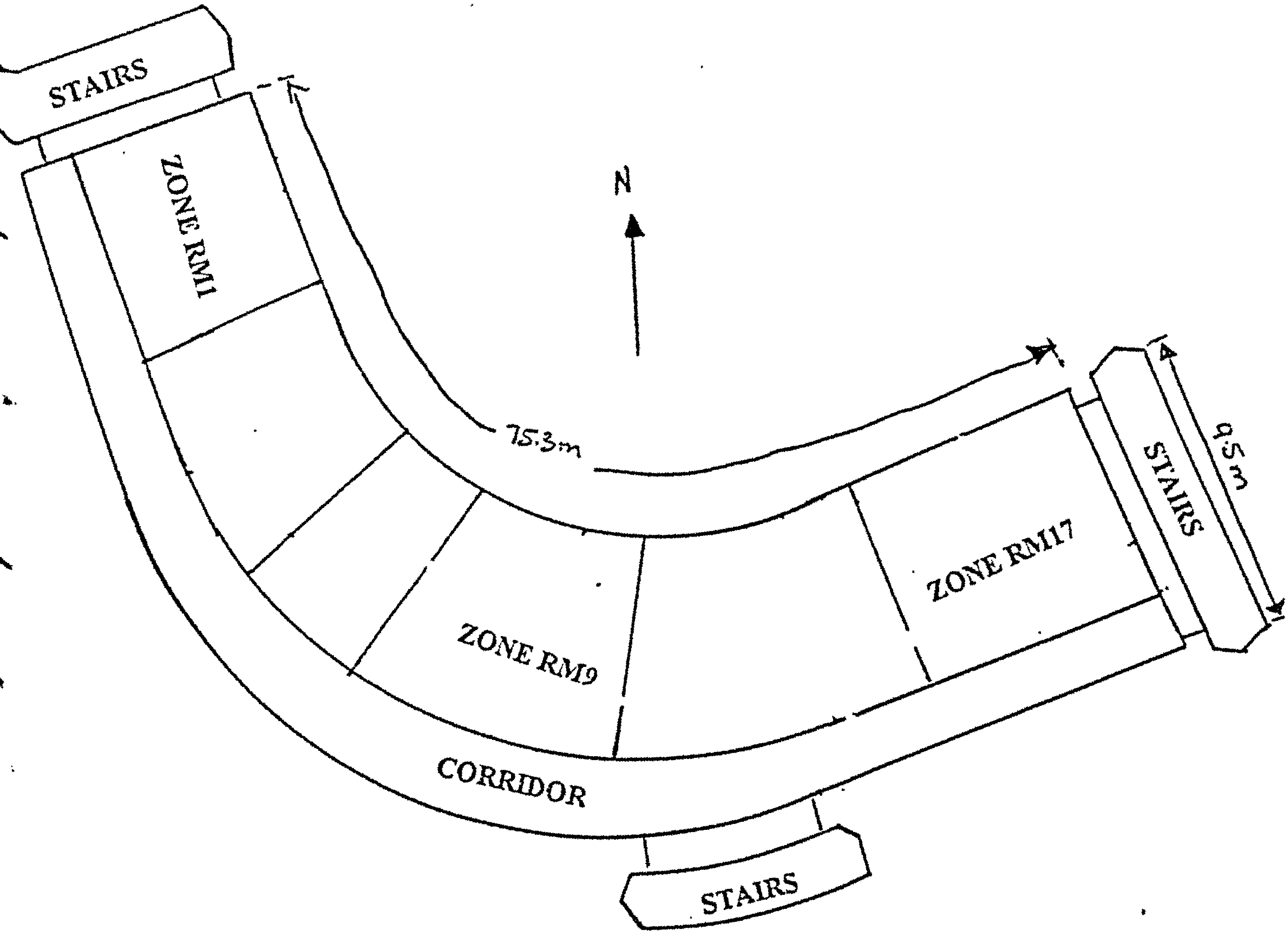

Figure 4.1: Floor Plan of Business Hotel

4.3.1b. Lighting

Rooms are equipped with 3x40W incandescent lamps and a 40W bathroom fluorescent fixture. The first floor mostly has 40W incandescent, dimmed lamps. The Basement and Second floors have 4-foot fluorescent or 8-foot fluorescent lamps. Other major power consumers are 2 boilers (2 x 72 kW rating) for water for the rooms and 2 identically rated boilers for the kitchen water . There are also 4 elevators with an estimated consumption of 50 kW each.

4.3.1c Air-Conditioning Zones

The building is divided into 6 air-conditioning zones, based on the separate air conditioning systems that serve different areas. The zones are:

i. East and West zones in Floors 15 to 19 served by the roof-mounted system

ii. East and West zones in Floors 3 to 14 served by the system in floor 2

iii. Floor 2 which basically contains the plant for Floors 3 to 14

iv. Floors 1 and Ground Floor which contain customer services facilities and the basement which contain maintenance services

4.3.1d Air-Conditioning System

Full air-conditioning is from two central air systems. Floors 3 to 14 are served by two variable volume(VAV) air handling units(AHU). The east zone consist of rooms 1 to 9 and the west zone rooms 10 to 18 on each floor. Each AHU is of 15kW capacity and both are served by a 562 kW Carrier Chiller (Model 30 HR160 0 910 AE) which also serves other small dedicated systems. The chiller is served by a Baltimore air coil cooling tower (model BAC VLT350).

Floors 15 to 19 are served by 2 roof-mounted 100% outside air cooling systems also zoned east and west. Two cross-connected, 56kW(95A, 390V and 1485 rpm) air-cooled chillers provide water to the units. The condenser water pumps and the cooling tower fans require 20 kW each. Each tower has 12 banks of motors of 0.75kW (2.15A, 380V, 1400rpm) rating. Roof-mounted chilled water pumps rated at 5.5kW (12.1A, 390V

1440rpm) pump chilled water at 250kPa with the return stop temperature of 9°C and a return start temperature of 16°C. The supply fans are each of 7.5kW each (390V, 15A and 1445 rpm) rating

The supply air temperature leaves the supply fans at 11°C and will be 15°C on reaching the dampers in each room. It is then heated by 1kW heater elements to the comfort temperature of 23°C. The heaters are controlled by a thermostat and they are individually adjustable. The temperature setpoints are (supply air : 14 to 19°C for outside air temperature: 12 to 25°C)

The ground floor system consists of 2 chillers each with 2 banks of 4 compressors rated at 45kW, 77A, 1500 rpm each. Only one bank of compressors per chiller work at any given time. The compressors in a bank are turned on in stages according to zone cooling demand. The chiller water supply pressure is 220 kPa and the return start and stop temperatures are 11°C and 8°C respectively. The 2 chiller pumps are rated as follows: supply: 2.2kW, 5.3A, 1400rpm and return 2.2kW, 4.8A, 1450rpm.

The chillers are served by 2 Baltimore Aircoil cooling towers model VXT85C each 10Hp(7.5kW) with the motor for the tower fans rated at 4kW, 8.7A, 1425 rpm. Their temperature setpoint is 26°C .

4.3.1e Air-Conditioning System Control Scheme

Each zone is served by a supply fan which distributes supply air to each room through air ducts mounted in the ceiling of the corridor The original design was of VAV pneumagrilles controlled by wall mounted thermostats. Each had a heating element sequenced on upon a fall of temperature after the dampers had closed. The cooling on/off switch on the thermostats operated the dampers bellows either fully open or fully closed . The design controls were as follows:

i. With outside air between 8°C and 16°C the supply air temperature was controlled by a hot water coil between 12°C and 21°C

ii. With outside temperature above 16°C, the supply air temperature was set to 12°C

The fresh and exhaust air dampers are interlinked to have identical openings and they remain at the minimum settings below 10°C and above 22°C. These dampers begin opening at 10°C and are fully open at 15°C. They remain fully open from 15°C to 20°C while cooling is available to remove solar and internal heat gains from the building. At 22°C the dampers begin to close to reduce the admission of heat gains into the building from the warm ventilation air. They reach their minimum setting at 22°C and remain there during hot weather.

The lower floors are served by a primary-secondary system with a 5.6kW primary pump and a 18.5kW secondary pump.

4.3.1f. Power Consumption

The hotel purchases power from ZESA under tariff 6 for high-capacity(>300 kVA) commercial ,industrial and mining consumers. Monthly demand and energy charges vary depending on time of day according to a rate schedule intended to approximate the time-of-use rate, with the peak period between 6 a.m. and 9 p.m.. The utility meters at the time of the survey did not measure the actual time of use but instead they assessed 65% of total monthly consumptions at peak rates. The existing apportionment of kWh to peak and off-peak period gave little incentive to defer loads to utility off-peak period. The true time-of-use meters whose implementation were under consideration make the demand charge significantly less during the off-peak period.

The loads discussed make the maximum demand of the building to be 920kW. However, the average demand has been found to be 735kW under a demand limiting strategy implemented using a computerised energy management system.

4.3.1g Retrofitting

The supply fans are now driven by variable speed drives using supply pressure as the control parameter. At the time of the visit the setpoint was 68.8 kPa but the possible range is 30 to 100 kPa enabling the speed of the drives to increase by up to 300%. The supply fans are set to supply an air flowrate of 4ach. The variable speed drives control the 3 phase squirrel cage induction motors rated at 15kW, 380V, 31.5A, 1455 rpm which respond to a pressure sensor output such that when they are 79.8% operational they draw 20.2A. Extensive changes was carried out on both the air-conditioning system and the inside building envelope at the time.

4.3.1h Consideration of Integrating Photovoltaics

The variable nature of the use of energy in this building means that specific loads can be targeted to be taken up by different energy sources. Already, solar water heating has been identified for the boilers. The retrofitting of the building was driven solely by the need to improve the energy efficiency of the building. The experience during that refurbishment was that more control can be applied on the air-conditioning system to minimise energy use. The building cladding system was not changed although it is almost three decades old. This gives an opportunity for photovoltaics to be considered in future when the recladding is inevitably done and the building-integrated photovoltaic technology hopefully considered viable. The main emphasis for photovoltaics integration was placed on the floors containing the lettable rooms because :

i. the data collected on them was more reliable,
ii. reasonable estimations could be made for those parameters not in the data collected
iii. their outer walls are best suited for installing PV systems because of their location and construction
iv. the load of the other floors were generally too complex for the great detail required for their proper simulation to be properly done and bound to change on a short time basis, while reasonable long-term predictions could be made for the rooms.

4.3.2 The Passively Ventilated Commercial Office Building

4.3.2a. Building Description

This building has 9 floors consisting of floors for commercial offices, the ground floor reserved for retail shops and 3 floors for parking. Two of the parking levels are underground and one is on the first floor. The floor plan of the building is shown in Figure 4.2.

Figure 4.2: Floor Plan of Passively Ventilated Building

The commercial offices are passively ventilated while individual mechanical ventilation is optional in the retail shops. The building is characterised by traditional construction techniques of heavy wall massing and small window area. It consists of a 9 inch double brick wall supported by 450,000 mullions of precast concrete. The precast units are usually expensive in the developed world, but their use was made economical in Zimbabwe because of the availability of local skilled but cheap labour to produce them. The finishes are generally light in colour. The building is used by over 2,000 office workers and many shoppers. Additionally 190 office kitchens are supplied by water heated by solar water heaters installed on the roof of the buildings. These are supplemented by electric heating elements when the solar energy levels are low.

4.3.2b Lighting

Office space can be provided by building a short squat building , a tall narrow building or a long thin building. The short building is less likely to be affected by external conditions; but its deep spaces will require constant artificial lighting. This creates unnecessary electricity consumption[18]. The tall building has access to natural lighting throughout, but will require greater capital cost to build and greater running costs for vertical circulation (lifts)

For the proposed site two long narrow plan office blocks of nine stories each, provided the required bulk and natural lighting possibilities. By orientating the blocks along an east-west axis, the solar gains were limited. On the covered street , the colour of the finishes are as light as possible so that natural light can penetrate the full depth, thus limiting the need for artificial lighting at the base. Additionally, all surfaces inside the offices have light colours so that both natural and artificial light sources are more effective. The combination of small clear glazing and light colours provides good natural light in combination with Harare's natural bright light. Light coloured blinds on the northern internal office windows also reflect light onto the darker southern offices thus improving natural daylighting .

Fluorescent fittings giving lighting at 25 W/m^2 were fitted into a false ceiling and were manufactured with slots so that heat generated by them enters the ceiling plenum rather than the occupied space.

4.3.2c Air-Conditioning Requirements

To achieve thermal comfort in the occupied space while limiting running costs, methods were investigated of limiting internal and external gains. These included ventilating the space to provide fresh air and remove heat and using night-time ventilation to further reduce night time temperatures.

i. Cooling Requirements

This commercial office building is passively cooled. The building design is such that it can have inside temperatures of 24°C with outside temperatures of 30°C. The room design temperature range is 20 to 26°C. External heat enters the building through the walls and windows. In a moderate climate such as Harare, the major source of heat is solar gains through glazing. Making use of a computer model to simulate the solar path together with various side and top shading devices ways can be established of stopping direct solar gains to the space. Solar heat gain also enters the building on the horizontal plane due to sky and ground reflectance. By limiting the glazed area to approximately 25% on the external north and south facades: a temperature difference of 1°C was found to occur between a well shaded 25% glazed north-facing facade and one with 50% glazing. The glazed areas on the internal faces are closer to 35% as the solar gains here are much reduced, and the daylighting is desirable to limit the use of artificial light. The combination of in-situ concrete and double thickness brick in the external walls provide adequate attenuation of the external temperature extremes. The generally light coloured finishes and blinds on the northern internal office windows stop solar energy entering the northern offices thus reducing their internal temperature.

The main source of heat inside the buildings is artificial lighting. The architectural form of the ceiling suggested the use of uplighting, but this is less efficient than downlighting. The computer model suggested a half degree rise in peak temperature when the lighting load was changed from $18W/m^2$ to $25W/m^2$ (a change from up to down lighting). Placing the starting gear out of the office space also reduced the heat gains by a further 15%.

ii. Ventilation Requirements

The decision to use natural or forced ventilation has a major bearing on the design of the building. Natural ventilation implies the opening of windows with consequences of noise and dust pollution, control of heat loss during winter and security. Additionally, control of ventilation rate in the space is left solely in the hands of the occupant. Since the building material has a thermal time lag associated with it, people will often open or close windows too early or late thus reducing the effectiveness of ventilating air.

For this reason it was decided that forced mechanical ventilation should be utilised. Fresh air enters the building plant rooms at the mezzanine level, approximately 10 metres above the ground floor, in the covered street. This is a pedestrian way with broad leafed plants which has cleaner air than the surrounding main roads. Simple filters are installed in the plant room to remove remaining large dust particles. The building has four major supply air zones. These correspond approximately to the four faces of the building. The zoning thus takes into account the varying external solar gain which will be experienced on each face. Ventilation is distributed via vertical ducts along the core of each office block(which is less useful in deep plan space). The air enters the voids in the concrete floor and is distributed to grilles on the external faces of the building under each window.

Daytime ventilation alone cannot provide sufficient means to remove heat from the building fabric. During the cool night, the ventilation system continues to operate, thus flushing additional heat from the building. The computer model was again used to determine the most effective ventilation rate, this being a balance between improved thermal conditions and the increased capital and running costs associated with a larger ventilation plant and distribution space. This indicated that little temperature improvement occurred if the air change rate was increased above 7 air changes per hour. Fans were selected to provide 7.2 ach which corresponds to 6 ach at sea level (Harare is 1500m above sea level). The increase in maximum room temperature was less than 0.5°C in comparison with higher exchange rates.

In addition low volume fans were also provided which give the occupied space about 2 ach. It was thought that internal conditions would be improved if the large fans were not used during the day time when the temperature outside was higher than the predicted internal temperatures. The computer model indicated a 1°C temperature drop in comparison with a constant air exchange rate. Incorporation of this feature had further advantages including:

i. restriction of large energy consuming fans to night time when electricity is supplied at a lower charge;

ii. attenuation of the supply air become less of a problem because the fans will be in operation when the building is empty and;

iii. the air speed through the supply air grilles is reduced thus encouraging displacement ventilation in the office space

Displacement ventilation consists of providing low turbulence air at low level. Since this air is cooler than the surrounding it drops to the floor and spreads out horizontally. Air that is heated by machines and people rises towards the ceiling and is replaced by the ventilation air. Lights at a higher level therefore heat the exhaust air, rather than at a low level. The overall purpose of this ventilation mechanism is to further improve comfort levels in the occupied space.

Exhaust air from the space enters high level bulkheads above the building core and the vertical shafts. These shafts are provided with concrete shunts and a high level smoke operated damper and thus acts as smoke exhaust shafts in the event of a fire. The shafts have a large cross sectional area and velocities are limited to around 2m/s so that exhaust fans have been eliminated from the design. Large openings at roof level discharge the exhaust air from the building.

iii. Thermal Massing

A specific and major aspect of the office design of this building was the exposure of the structural concrete elements to the occupied space. The exposed concrete ceiling was designed as an articulated surface, to increase the exposed area. The increase in the surface area provides an additional ability to absorb room heat gains.

The voids in the concrete floor were created by first pouring insitu concrete onto curved metal shuttering. Thus forming the exposed ceiling of the office space. This concrete has a thickness varying from about 200mm to 450mm and provides a thermal time lag of more than 5 hours between its upper and lower surfaces: its corresponding heat capacity is approximately 450kJ/°C for each square metre of the office floor. The radiant gain from the fluorescent lighting at 25W/m^2 corresponds to about 450kJ over 10 hours of operation. Thus if all this heat were absorbed into the slab, its average temperature would rise by 1°C. Due to the inherent time lag of the concrete, the actual surface temperature of the concrete will rise above this average. The upper section of the void is created by placing concrete stools on the surface of the in situ floor. These precast stools are provided with teeth to increase their surface area and downstands which induce turbulence in the incoming air. The combination of these devices provides an increased heat transfer rate between the concrete and the ventilation air. Since the concrete temperature remains around 20°C, this heat exchange will serve to cool the incoming air in the summer and heat the air in winter.

iv Heating

Room heaters are provided for winter months. These are switched locally, so that occupants can control the heat in the office, and centrally, so that the overall consumption of electricity and load shedding can be controlled by the building management. In winter the low volume fans are used thus limiting the energy required to heat the incoming air.

4.3.2d Comparison With Fully Air-Conditioned Commercial Office Buildings

Studies were made into temperatures found in Harare over the last ten years. This information was extrapolated to predict the temperatures that would be obtained during a typical year. The study indicated that internal temperatures would exceed the upper band of summer comfort (27°C) for 5% of the year. An air-conditioned building is normally designed to maintain a resultant temperature of 25°C over 97.5% of the year. Consequently, the mechanically ventilated system provides reasonable comfort conditions throughout the year, but not to the same degree as an air-conditioned building. However, it is only during certain days in October when temperatures can be as high as 29°C that space conditions are beyond acceptable comfort conditions in this building.

4.3.2e Cost Considerations

The capital cost was 65% that of an equally sized conventional building with full air-conditioning and its running cost is 20% of such a building. An air-conditioned system of similar size would have cost approximately Z$25million with Z$8.5 million in foreign currency while the ventilated system cost Z$3 million with Z$120,000 in foreign currency. The maximum demand on the electrical supply for the air-conditioning system would be approximately 1,000kW(equating to Z$500,000 per annum). The office ventilation system on this building has a maximum demand (excluding electrical heating) of under 20kW.The majority of the components used are of local manufacture with a foreign currency content of less than 10%.This can be compared with more than 25% in average mechanical installations. The components, including the control elements, are relatively simple devices and therefore the system is simple to maintain. Renting the office space costs Z$60/m^2 compared to Z$75/m^2 in conventional buildings. The cost of the wall per unit area is $Z600 compared to Z$1700 for buildings with solar shield glazed curtain walls.

4.3.2e Retail Units

The retail units in this building comprise 5,000m^2 of shops surrounding the covered street at ground and first floor level. Shops with high internal gain, such as electrical outlets, will generally require air-conditioning whilst shops with low internal gains, such as bookstores, can be ventilated only. All shops have the facility for installing air-conditioning but a simple ventilation system has been included. Ventilation will provide adequate comfort levels for most outlets. So far only one outlet has requested for an air-conditioning system.

The external walls and the shop fronts are shaded with overhangs to limit penetration of solar gains. Ventilation air enters the shop fronts via permanently open grilles thus allowing night time ventilation. Extract fans remove the heated air from the ceiling plenum and exhaust it to the outside. Fans are controlled by shop owners. In summer they are left on during the night, whilst in winter they are turned off for most of the time.

4.3.2f Covered Street

The covered street between the two office blocks provides shade and protection from wet weather. These advantages created other problems which were dealt with during the design process. These were: i) smoke and fire control, ii) summer overheating, ii) reduction in light levels in internal facing offices and ii) acoustic control

Studies of the required ventilation rate were dominated by concerns related to fire and smoke spread. The glazed roof over the covered street was raised over four metres above the adjacent office blocks on concrete beams. The sides were left open so that heated air can escape along the full length of the atrium roof. The free area of 800m^2 will ensure that hot air does not build up at the top of the covered way. Additionally the ends of the mall were screened to stop rain from entering the covered space. Peak temperature rises of about 3°C above ambient can be expected without any additional solar screening. When shading is hung between the high level beams, the internal temperature should not rise substantially above air temperature. Additional improvements in thermal comfort were to be obtained when the atrium was painted in light colours as this meant the solar gains would be reflected away from the fabric. This would also improve light levels throughout the adjoining spaces.

4.3.2g Consideration of Integrating Photovoltaics

The design of this building marks the increasing proliferation of more energy conservation measures in the commercial building design in Zimbabwe. Its emphasis on features for reducing the effect of solar energy on heat gains in the offices in the form of shading systems provides a ready-made mounting facility for photovoltaic panels. The successful utilisation of solar water heating suggests that there is scope in aiming for a building design utilising integration of different energy sources. The problems associated with the need for daylighting and reducing solar energy gains in the glass covered street whose solution has been suggested to be using glass with a light colour also gives a case for translucent photovoltaic panels both in energy and cost terms. The relatively small air-conditioning load can easily be catered for by a photovoltaic system on the building as estimations carried out in Chapter 3 show that even by conservative standards this load is only a fraction of the power that can be generated from a photovoltaic system mounted on the building. The size and shape of the building makes the potential of PV on it such that even loads like lighting can be powered by this energy source.

4.3.3. The Non-Air-Conditioned Government Office Building

This is a 20 storey government building with an east west orientation and located on the north-western outskirts of Harare city centre. It was constructed in the late 1970s, and is entirely occupied by government offices. Its operation schedule is of a typical office building. However, it accommodates a transient occupancy consisting of a large number of people constantly moving in and out because of the public services available in it. The occupancy was considered static for counting purposes but they were attributed with energy generating capacities of a continually mobile occupancy. The building is not centrally air conditioned. As a result there is a tendency to use room fans on hot days in September and October. Similarly, there is a tendency to use individual electric heating units in winter, in July and June. Usage of these units does not follow a uniform pattern and it is difficult to account for them when quantifying the energy loads of the whole building. A typical floor can be subdivided into 5 distinct zones. As shown in Figure 4.3.

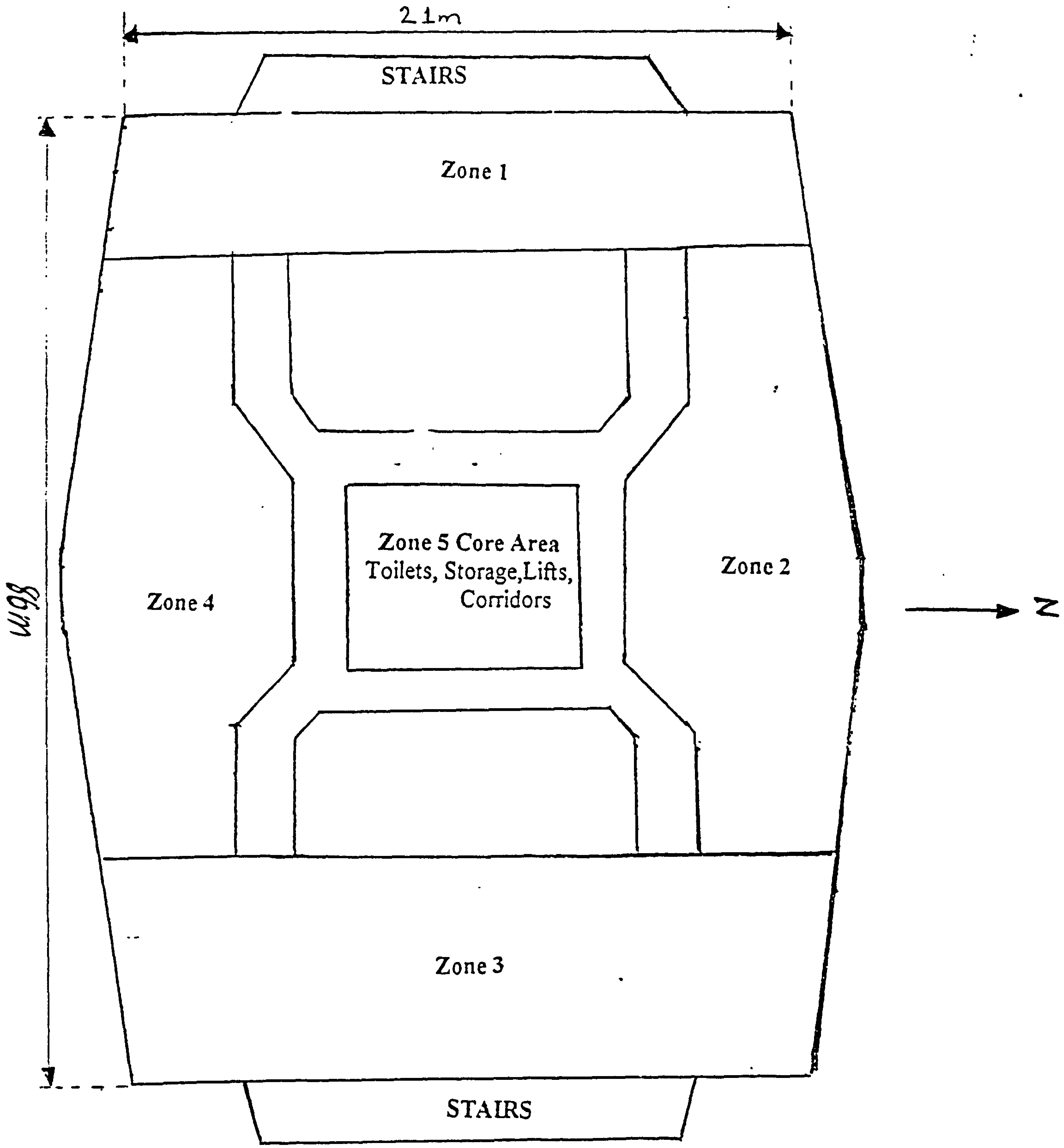

Figure 4.3: Floor Plan of The Government Office Building

The central zone is where services such as lifts, toilets and kitchenettes are located. This area was considered as one thermal zone for analytical purposes due to the variant nature of these services and the numerical immensity of the sub-areas. The central zone is surrounded by 4 outer zones which are separated from each other and the central zone by a 20cm brick wall which is plastered and painted. The outer zones are separated from each other and the corridor by partitioning board. The outer walls are made from 1m high 22.5 cm thick concrete wall with metal panelling between the columns. The windows are 1.5m high and have clear single glazing. They run the length of each north and south wall and are only interspaced by concrete columns. They are also 50% openable.

The main electrical energy consuming services are the lights, electronic equipment and eight lifts. Each lift has an estimated peak consumption of 47kW. The lighting system consists of mainly 40W fluorescent lamps.

4.3.4 The Prestige Modern Commercial Office Building

4.3.4a. Building Description

This is an octagonal twenty-six storey building with the sixth floor to the twenty sixth floor entirely covered by a 80% solar reflecting glass curtain. The basic construction of the external wall is of 230mm brick 3m high on concrete slab.. The ground to fifth floors, however, have polished granite cladding around their walls instead of the glass curtain. The glass curtain and the wall are 0.5m apart giving a passage for air to be pumped up the length of the building, making it behave like a plenum. The windows are of clear double glazing and 50% openable with a window wall ratio of 0.33. They run the whole length of each wall. The internal walls between adjacent zones is made of 15% plasterboard 2.7m high. Those between perimeter zones and central zones are made of 190mm brick The total office area per floor is 500m^2 with 80m^2 allocated to the lobby and 170 m^2 taken up by the toilet and stairs. Each office floor has a 0.5m deep suspended ceiling made of acoustic tiles. The floor plan of this building is shown in Figure 4.4.

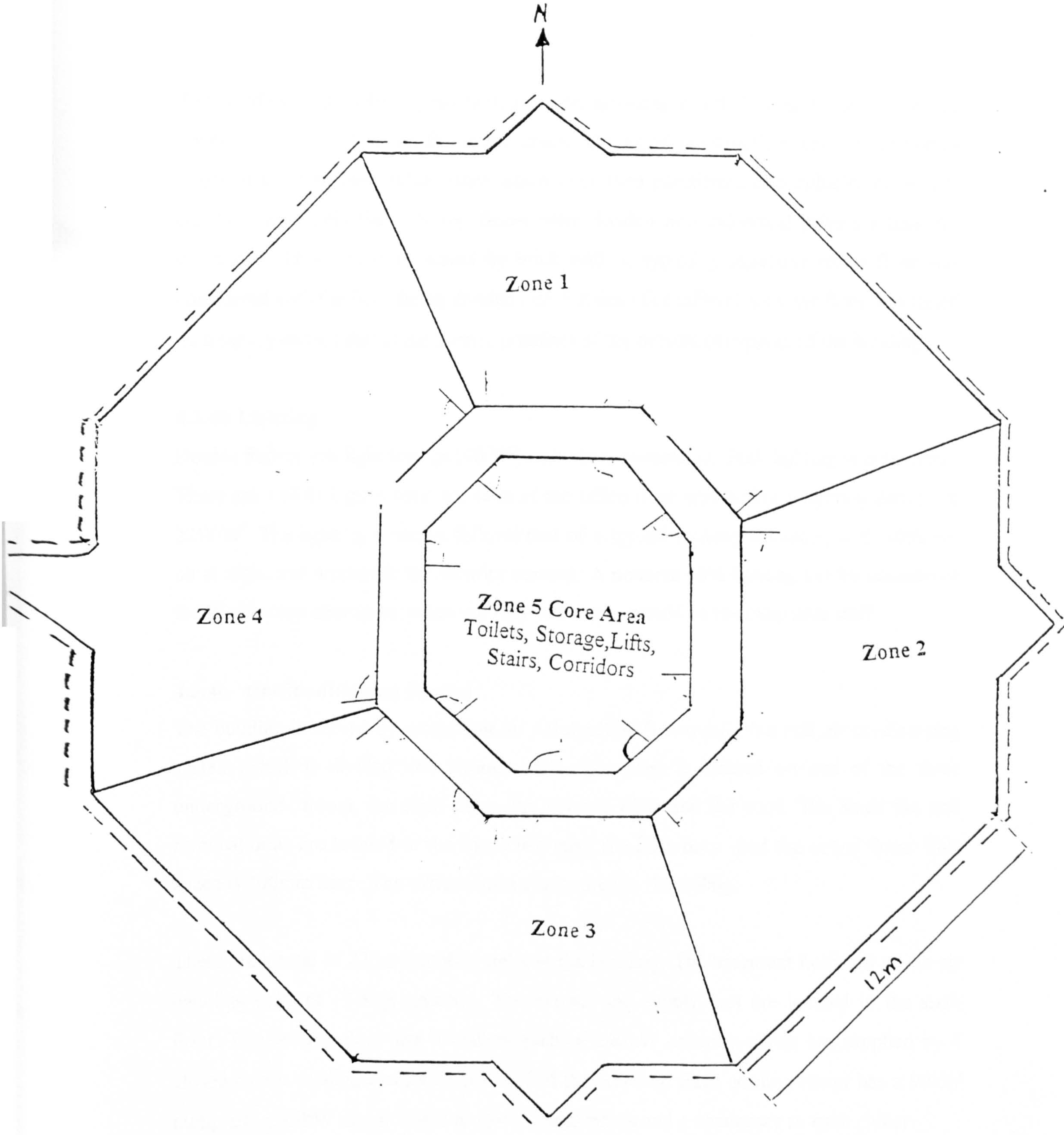

Figure 4.4: Floor Plan of Prestige Modern Building

The building is a multipurpose building with activities of retailing and banking on the lower floors and offices on the upper floors. The initial construction was for the middle floors to be open plan office zones which were then partitioned into cubicles for mainly clerical work. Only the very top floors were divided into individual private offices for executives. These were separated by brick wall. A typical prospective office floor was considered with the floor being divided into 5 zones. The schedules on the floor was based on a survey carried out at the former premises of the present occupants of the building.

4.3.4b Lighting

Double fluorescent light fittings (40 W) only were considered. Task lighting was ignored. There are 140 fittings in total for each of the office floor area giving a lighting density of 22W/m^2. The lighting schedule follows that of a typical banking schedule, with 10% left on at night and weekends for security reasons. A nominal 40% lighting can be considered for Wednesday afternoons when the only occupants would be the executive staff.

4.3.4c. Air-Conditioning System

The building is served by a constant air volume(CAV) two-pipe fan coil air-conditioning system which is divided into various units. The plant is located on one of the three underground floors, the sixth floor, the seventh floor and the roof. The small fan coil terminal units are located in the space between the false floor and the actual floor. This space is 400mm deep. The extract units are located in the ceiling.

There are a total of 22 air-handling units in the building. The basement holds 10 of the air handling units of 7.5Hp capacity. The extract and supply fans are located in the sixth floor. The seventh floor has 6 chillers each of 240kW capacity which are supplied by 4 closed circuit cooling towers on the roof of the building. Each cooling tower has a 90kW pump and a 15kW motor There are two compressors and a condenser to each chiller.

The air-conditioning system employs a central control with the number of chillers running determined by the cooling demand. The room temperature setpoint is 20°C

4.3.5 The Tenant Occupied Executive Commercial Building

4.3.5a Building Description

This is a 17-storey building with a gross floor area of 15340m^2. It has bronze-tinted double glazed windows with a window to wall ratio of 0.33 on all sides. Its perimeter zones are therefore equally exposed to incident solar radiation regardless of the orientation of their external walls. This is similar to the Prestige building, but digresses from the conventional building design which tend to have more glazing on the north and south sides than on the east and west sides. The walls are made of brick on concrete slab, and they have a weather protection cladding. Almost all the office areas are perimeter zones divided into individual offices by gypsum board. The central zone contains ablution facilities, the lift area and kitchenettes for beverage preparation. It is separated by an internal brick wall from the perimeter zones.

4.3.5b Air-Conditioning System

The environment within the building is kept at comfort levels by a full multizone dual duct air-conditioning system. The duct system is mounted in a half-metre deep ceiling. The air-conditioning system consists of two 500kW chillers located on the sixth floor which are served by two roof mounted cooling towers. The building also has baseboard heating which is only switched on in the middle winter months of June and July. This is controlled by proportional thermostats. The plant runs throughout the year except during maintenance periods. It is operated on a night setback mode, with a start-up at 7.30am and switch-off at 4.30pm. The plant operates with a setpoint of 23°C and a bandwidth of 3°C.

4.3.5c Lighting

The lighting system consists of fluorescent fittings placed close to the air-conditioning ducts so that their heating effect on the room air is reduced.

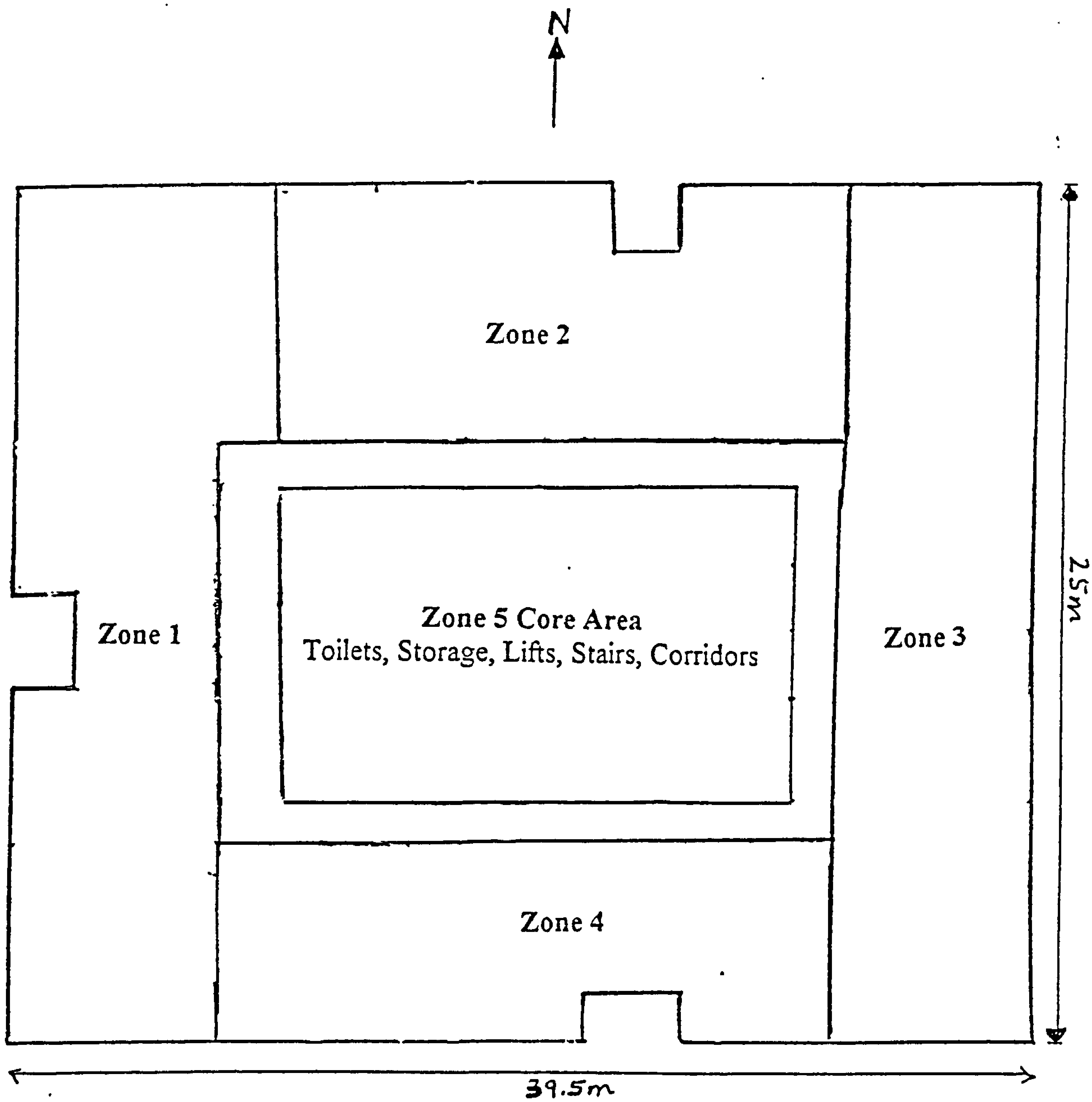

Figure 4.5. Floor Plan of Tenant Occupied Building

4.3.6 Survey of Architects and Building Engineers

The majority of the architects interviewed agreed that the moderate climate in Zimbabwe offered opportunities for designing buildings without full air-conditioning systems. They however conceded that their designs were driven by the demands of their clients who claimed that a full air-conditioning system in a building was an effective marketing tool in attracting high profile tenants most of whom could easily foot the renting bills inflated by passed-on energy costs. They also pointed out that there have been cases where the architect and the building engineering consultant have been able to persuade the owner that a design excluding full air-conditioning system was the best option. The result of this was that there was a trend whereby a considerable number of buildings owned by companies occupying them were not fully air-conditioned, while those let to tenants were mostly fully air-conditioned. There was a strong consensus however that individual air-conditioning units such as heaters and desk fans tend to be used in naturally ventilated buildings.

4.4 Energy Modelling Techniques

4.4.1 Sources of Data For Energy Modelling

It has already been noted that building data must have the breadth necessary to accurately describe major segments of the building stock, in which new technologies will ultimately be placed, and the depth necessary for detailed energy studies[19]. Energy simulation models have been identified as the pre-requisite vehicles for the initial stages of energy technology assessments on buildings when the building data available is partially complete[19]. Consequently, there is a need to extend the results of the cluster analysis of the building stock in Chapter 3, so that energy simulations can be carried out and the results so obtained calibrated using metered data and annual energy consumption from billing records. Accurately analysing the energy use of building populations is difficult for a number of reasons related to deficiencies in the data available. Where insufficient information to drive a simple energy model is available, it is necessary to draw on a number of different supplementary data sources such as building standards, building technology literature, submetered data and professional judgement[20]. An energy model

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separately and modified by thermal response factors appropriate to its frequency. The system response can be obtained by summing individual effects of the separate harmonics with respect to the mean condition.

- **Numerical Methods**

These methods are composed of two main techniques: finite difference and finite element, although the former is the technique widely applied to building energy modelling. They are most suited to time-varying problems of high order and give a solution to the partial differential equation governing the heat transfer. However, they are only valid for preselected discrete points with properties characteristic to some finite region. The finite difference techniques approximate the derivatives of the heat equation using either a truncated Taylor series or a by applying the principle of energy conservation to small control volumes. The finite element techniques solves the heat equation by minimising some related integral quantity using calculus of variations

4.4.3 System Performance Modelling

Air-conditioning and refrigeration processes are basically heat, mass and work transfer processes. Their processes are well established[34] and applied extensively in determining the rates of heat, mass and work transfers in air-conditioning equipment The working principles of air-conditioning equipment and components are simple, but the geometric configurations are complicated and the fluid flow complex. Therefore, rigorous modelling would be complex without simplifications such as deriving mathematical models by applying curve-fitting techniques to equipment data supplied by the manufacturer[36]. The model so obtained however tends to be design and size specific. For some types of equipment, models can be formulated from fundamental principles provided the details of construction and accurate data of heat and mass transfer coefficients is available[37]. However, the coefficients become increasing difficult to obtain for all situations of the air-conditioning system performance. Consequently, many mathematical models have been developed for modelling various kinds of air-conditioning system equipment and components. Many of these models have been fortunately developed into standard modules of computer simulation programs such as DOE2[38], TRNSYS[39], HVACSIM [40] and ESP[41]. These programs allow models of the components to be constructed and used to predict system performance.

4.4.3a The Available Simulation Software

There are many available energy simulation programs. Some of the leading ones are APACHE, BLAST, DOE-2, ESP, SERI-RES, TAS and TRNSYS. They use a mathematical model to simulate the heat flow and storage of a building structure. The most common are the finite difference models used in APACHE and SERI-RES, and the response factor models used in BLAST, DOE-2, TAS and TRNSYS[42]. Some have been traditionally been used on both workstations, mainframes and personal computers e.g. TRNSYS while some could only be used on workstations e.g. ESP. This is important because personal computers are available to almost all personnel who may be interested in building energy analysis, while this may not be true for workstations. Fortunately, the power of the personal computer has been increasing tremendously and it is hoped all the simulation programs can be run on them.

i. BLAST

This public domain program calculates hourly room loads using a detailed surface-by-surface and room air heat balance [43]. It simulates the system to predict hourly fan energy consumption and chilled water demand using algorithms close to first principles. The subprograms for the building, fan system and plant run in sequence but do not interact dynamically. Its use of few approximations, however, makes experience and judgement less important [44].

ii. ESP

This public domain program is widely used in Europe. It uses full geometry to explicitly model internal radiant heat transfer and reduce user inputs. Use of separate convective and long wave radiation transfer allows full definition of heat and temperature inputs [45]. It has however been found not to have the facility for temporary software changes by the user and could not simulate lighting. Complex datasets made its run times long[46]. Since the initial comparisons of modelling software packages were made the problem of underpredicting heating energy demands due to inaccurate interior solar absorption simulation has been solved by making algorithmic changes. This program has also been vastly improved by its use for sensitivity analyses of photovoltaic facade elements on the ELSA building at the EU Joint Research Centre in Italy under the PV-HYBRID-PAS Joule project[47]

iii SERI-RES

This has been widely used in Europe and the USA. It combines convective and radiant transfer to simplify the model making the radiant:convective ratio fixed. Temporary changes to the code by the user is difficult to implement and user inputs are heavily dependent on user experience. It also lacks treatment of plant and control, internal radiation and window capacity. This limits its performance assessments[48]. Its limitations on following monitored data has been highlighted, though it was found to exhibit similar trends[49].

iv. TRNSYS

This is a modular simulation program which requires a detailed data set. Individual components of a system are modelled in a modular way using type routines. Therefore, it allows a very flexible definition of any system under investigation. It allows the component type routines to be changed and user-defined component mathematical models to be added to its library[50]. It is excellent for detailed analyses of time-dependent systems that cannot be treated by standard options[51]. It has also been suggested to be the most advanced simulation program for active solar energy systems[52] . It requires some degree of expertise in FORTRAN to use it and detailed knowledge of the plant as well as the building envelope.

v. APACHE

This is primarily a commercial package and its use is confined to the UK. However, it can give more accurate results than some respected packages, and it has been used at the University of Northumbria with satisfactory results. Therefore, it can be used to check the input of the program chosen as the vehicle for analysis[53].

vi. DOE2

DOE2 is a generic program which is used widely in research [54]. It has been verified by experimental tests on actual buildings [55] and is considered a standard in energy analysis computing [56]. It consists of 4 sequenced subprograms LOADS, SYSTEMS, PLANT and ECONOMICS which interact dynamically[57].

LOADS calculates the first thermal load approximation of a building based on a constant setpoint temperature after modelling the building in a hierarchy of three-right-handed Cartesian co-ordinate systems consisting of the building, space and surface respectively. These systems are related to each other by simple translation and rotation. This feature can be used to model fixed and movable shading features.

SYSTEMS simulates the operation of the equipment and systems that distribute the cooling and/or heating energy directly to the spaces being conditioned and also the control of temperature and humidity in these areas. It also permits parametric runs. In one computer run calculations can be made for up to four different plant assignments . One zone can be assigned more than one system thereby allowing the effect of different system parameters to be analysed in one run and thus reducing the computer time. PLANT calculates the performance of the primary conversion equipment as chosen by the user based on operating conditions and part-load performances and using hourly results from LOADS and SYSTEMS. ECONOMICS may be used to compute life-cycle costs.

Its immensity however may make it laborious to work with or alter. Therefore, it is best used for analysing results it generates with only basic low level changes to the code itself. It requires a very accurate input file otherwise results inconsistent with the intended building are observed. Therefore, another package has to be used to check the validity of the results of one of the buildings in the subset of the exemplar buildings being investigated . This may also assist in ascertaining the ability of modelling the common lighting parameters faithfully, many of which, for DOE2, must be previously known or calculated .

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The occupancy for the passively ventilated building was estimated from the fact that the building has 2,000 employees, and from discussions with the building engineers, Ove Arup and Partners and architects, Pearce Partnership Architects as well as visiting a typical floor within the building, courtesy of the architects and the proprietors, Old Mutual Properties. The details of occupancy of the tenant-occupied executive commercial building was obtained from the same building engineers and the proprietors of the building as above and from working in the 9th floor of this building for 4 months. The details of the government building was obtained from initial work done by the department of energy of Zimbabwe.

4.4.4.b. The SYSTEMS and PLANT Subprogram Input

The most important parameters required here were

i. Zone temperature setpoints and thermostat types
ii. Fan schedules and capacities
iii. System running schedules (switching on and off regimes)
iv. Assignments zones to systems and defining air-conditioned zones
v. Chiller, Fan and Pump Sizes and schedules

This data was obtained from the design engineers and maintenance engineers, and from site visits of the plants.

4.4.4c Parametric Runs Made

The following sets of runs were made

i. LOADS subprogram alone: to establish the cooling loads without the effect of the mechanical ventilation
ii. LOADS, SYSTEMS and PLANT: to establish the building cooling load under the existing design setpoints
iii. Chillers and cooling towers left to be sized by the plant: to observe the energy that would have been consumed if the plant sizing was optimal.

The following output parameters were recorded;

- Outside air temperature, Zone temperature
- Incident solar gains, Zone solar gains
- Cooling and Heating Loads
- Energy Consumed by the plant

4.5 Results of Building Energy Simulation

Comparison of DOE2 results and APACHE results

DOE2 APACHE

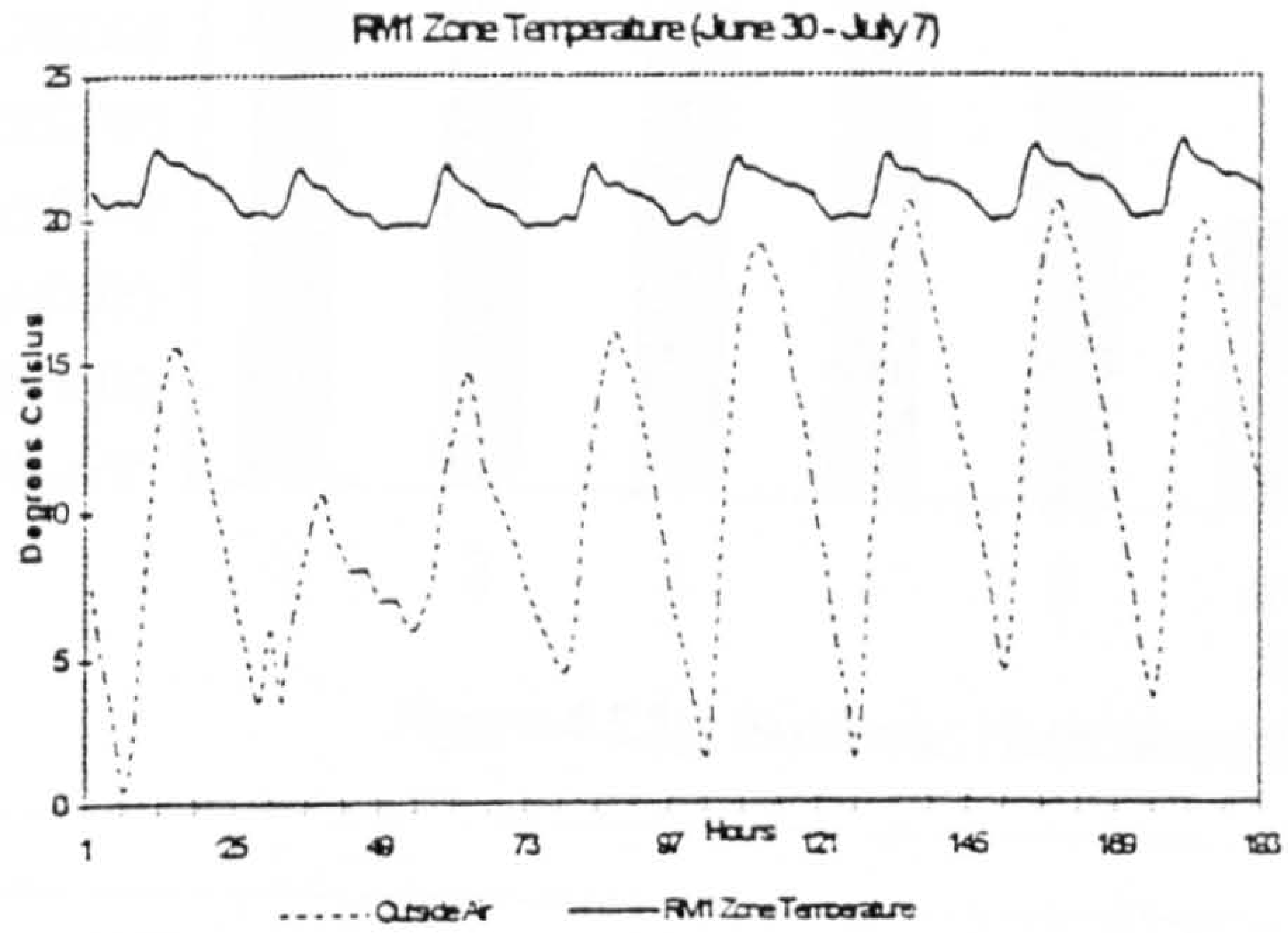


Figure 4.5.5a Business Hotel: Zone RM1 Temperatures (June 30-July7)

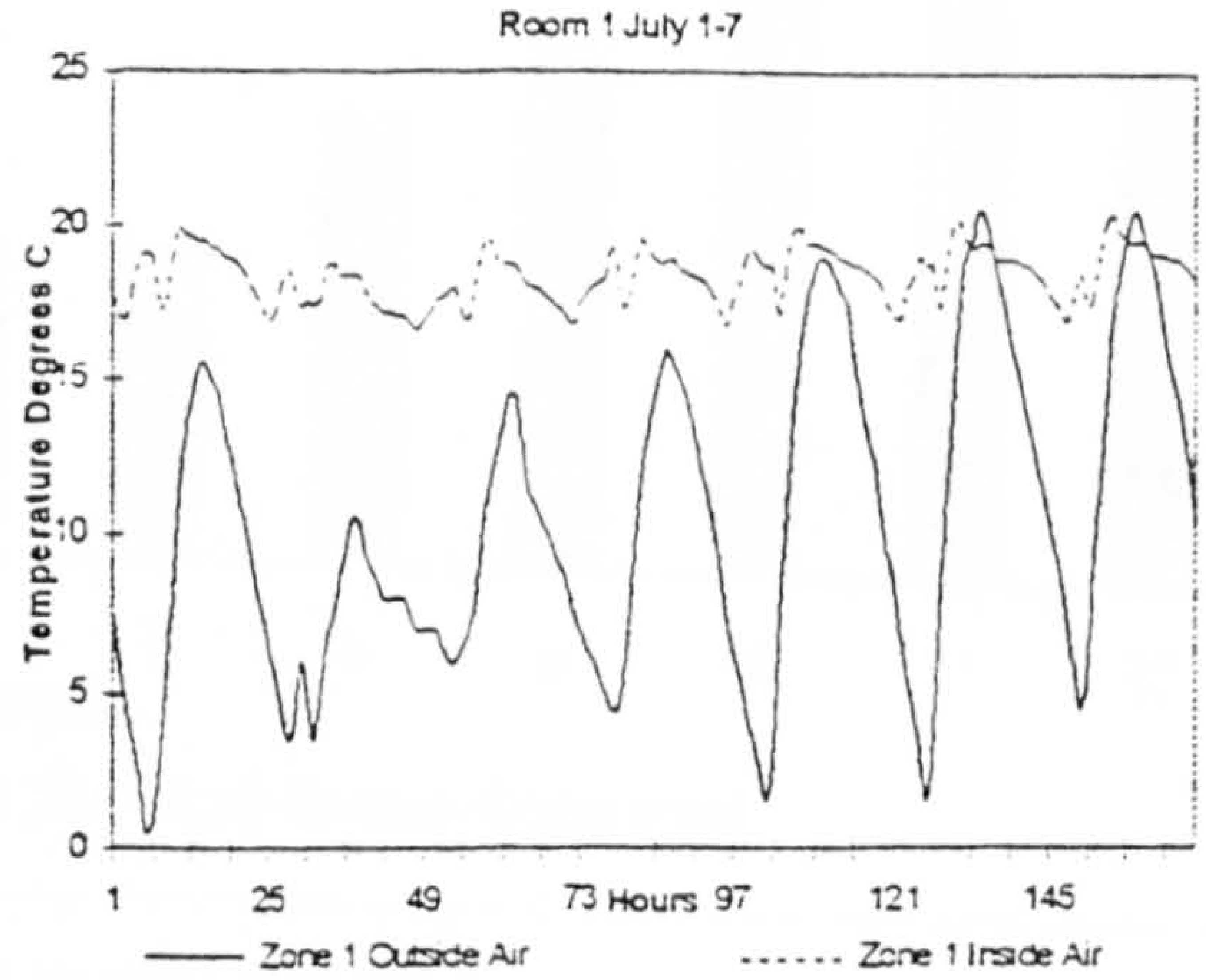


Figure 4.5.5b Business Hotel: Zone RM1 Temperatures (July 1-July7)

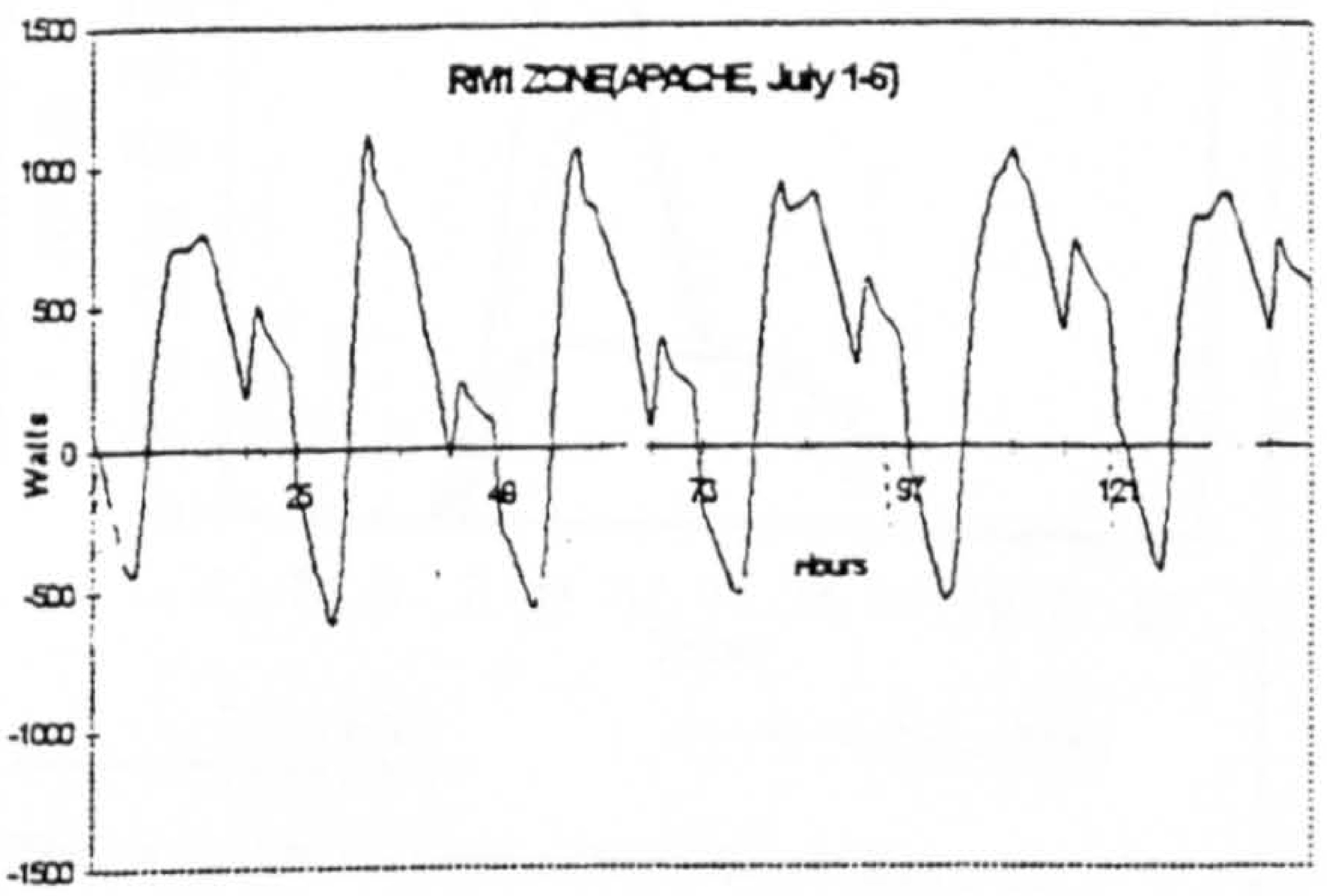


Figure 4.5.5c Business Hotel: Zone RM1 Sensible Cooling Load (July1-July6)

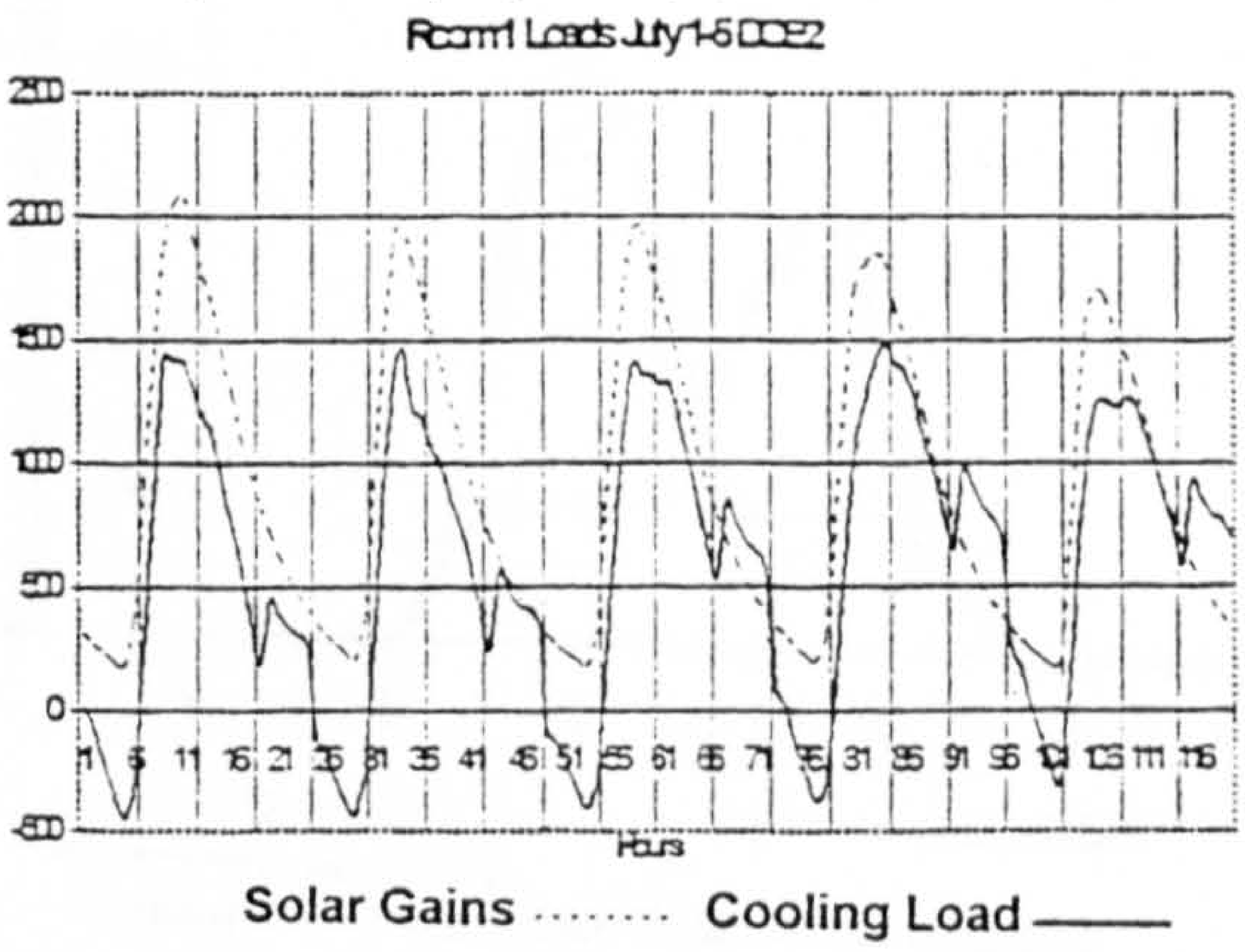
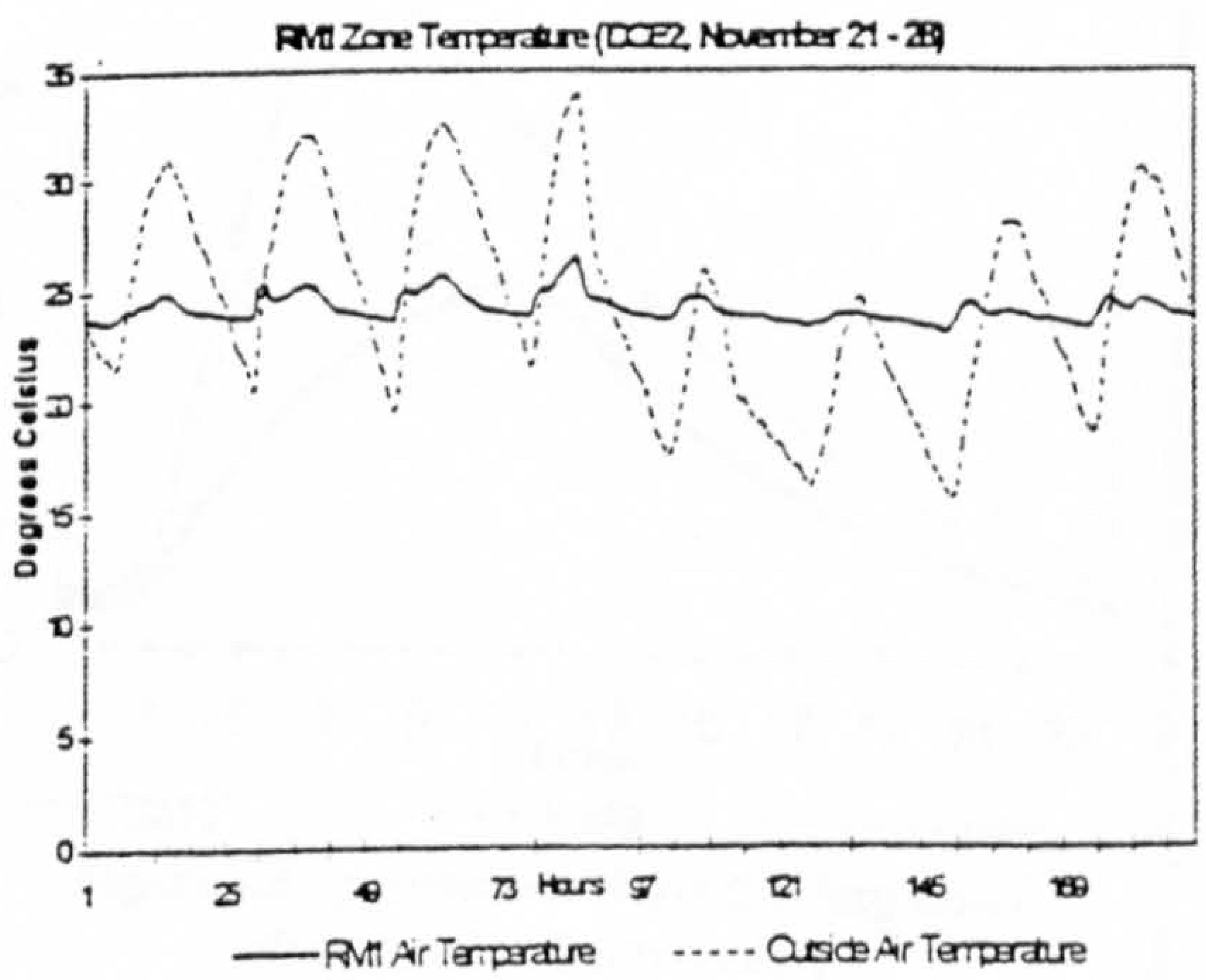


Figure 4.5.5d Business Hotel: Zone RM1 Sensible Cooling Load and Solar Gains (July 1-July5)

Zone Temperature(APACHE)



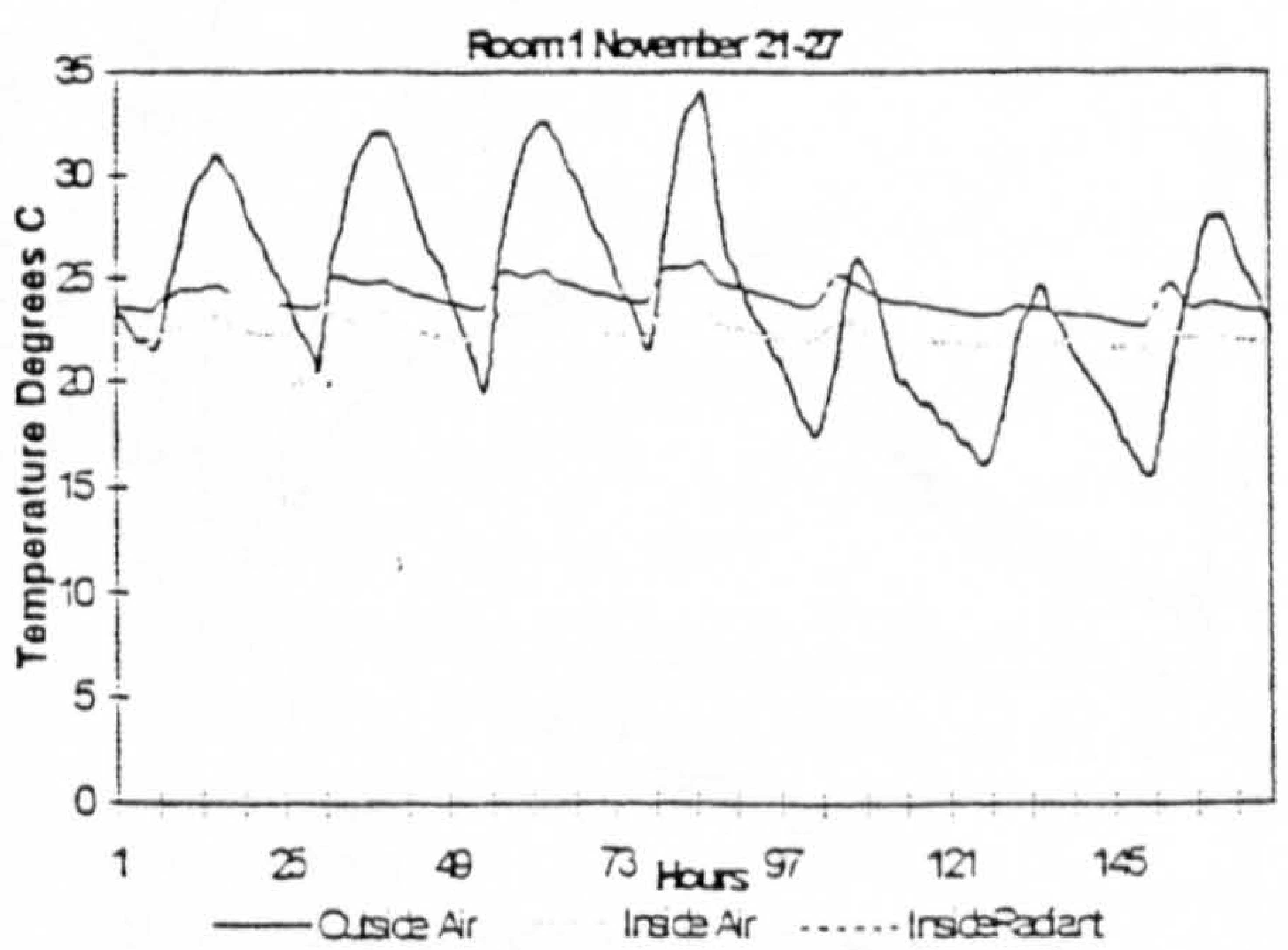


Figure 4.5.5e: Business Hotel: Zone RM1 Temperatures (November 21-November28)

Figure 4.5.f Business Hotel: Zone RM1 Temperatures(November 21-November28))

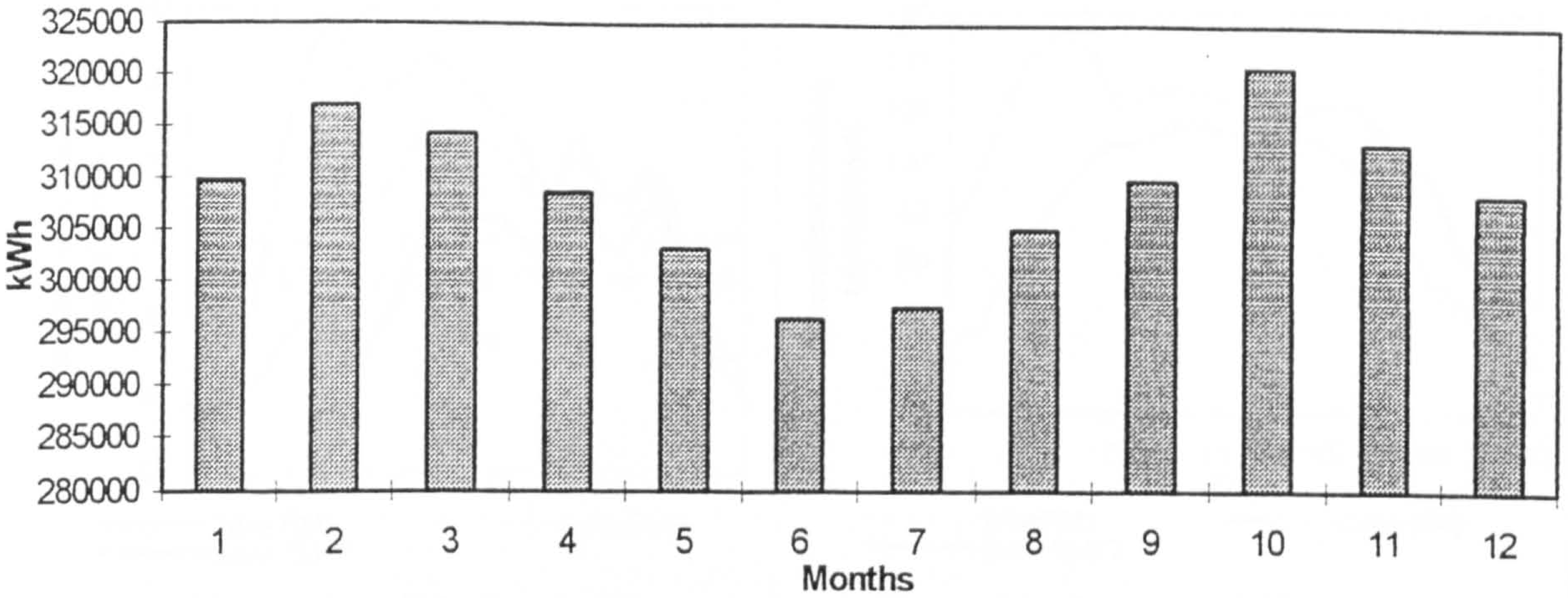


Figure 4.5.1g: Business Hotel Monthly Electrical Energy Consumed

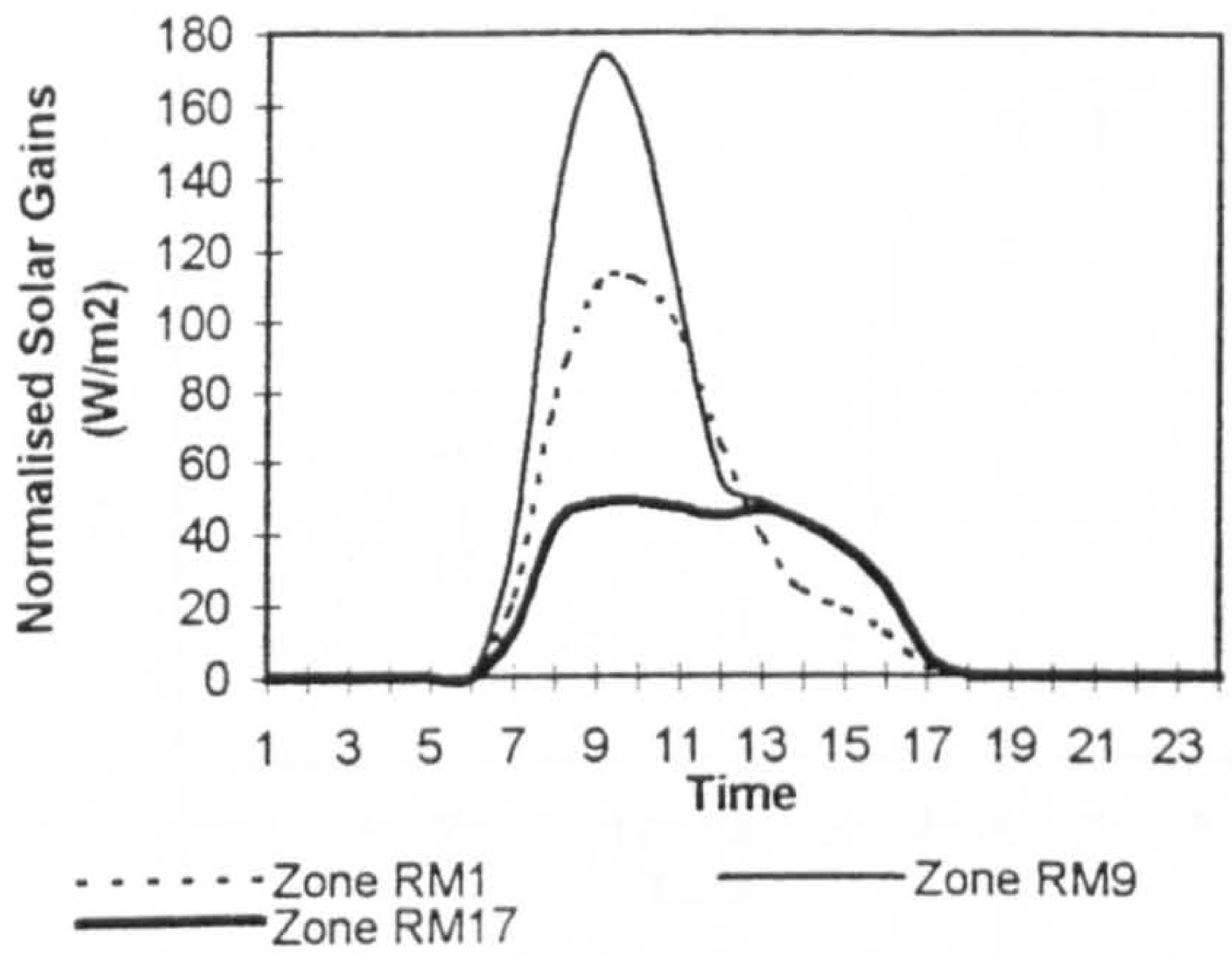


Figure 4.5.1h: Business Hotel Solar Gains in July

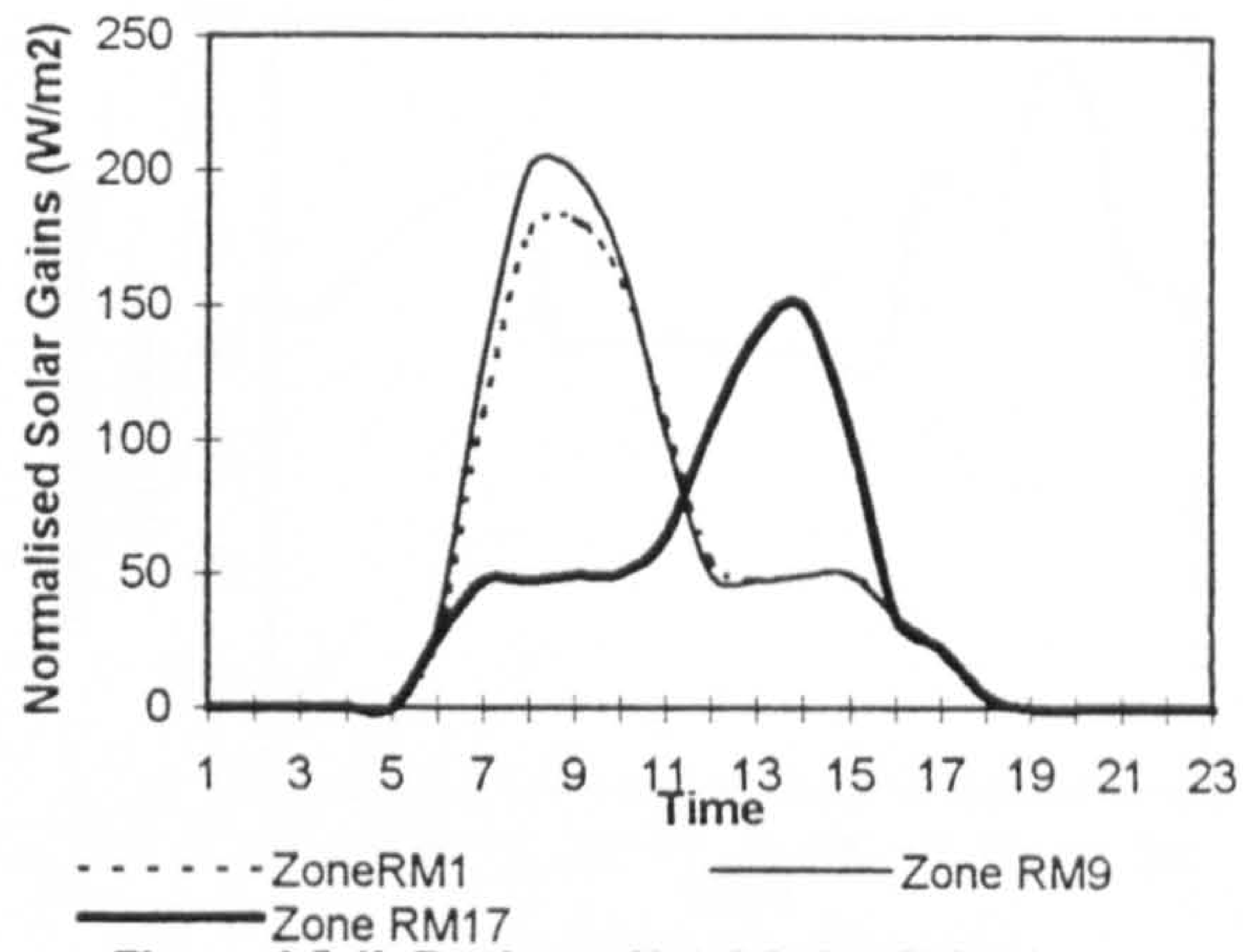


Figure 4.5.1i: Business Hotel Solar Gains in October

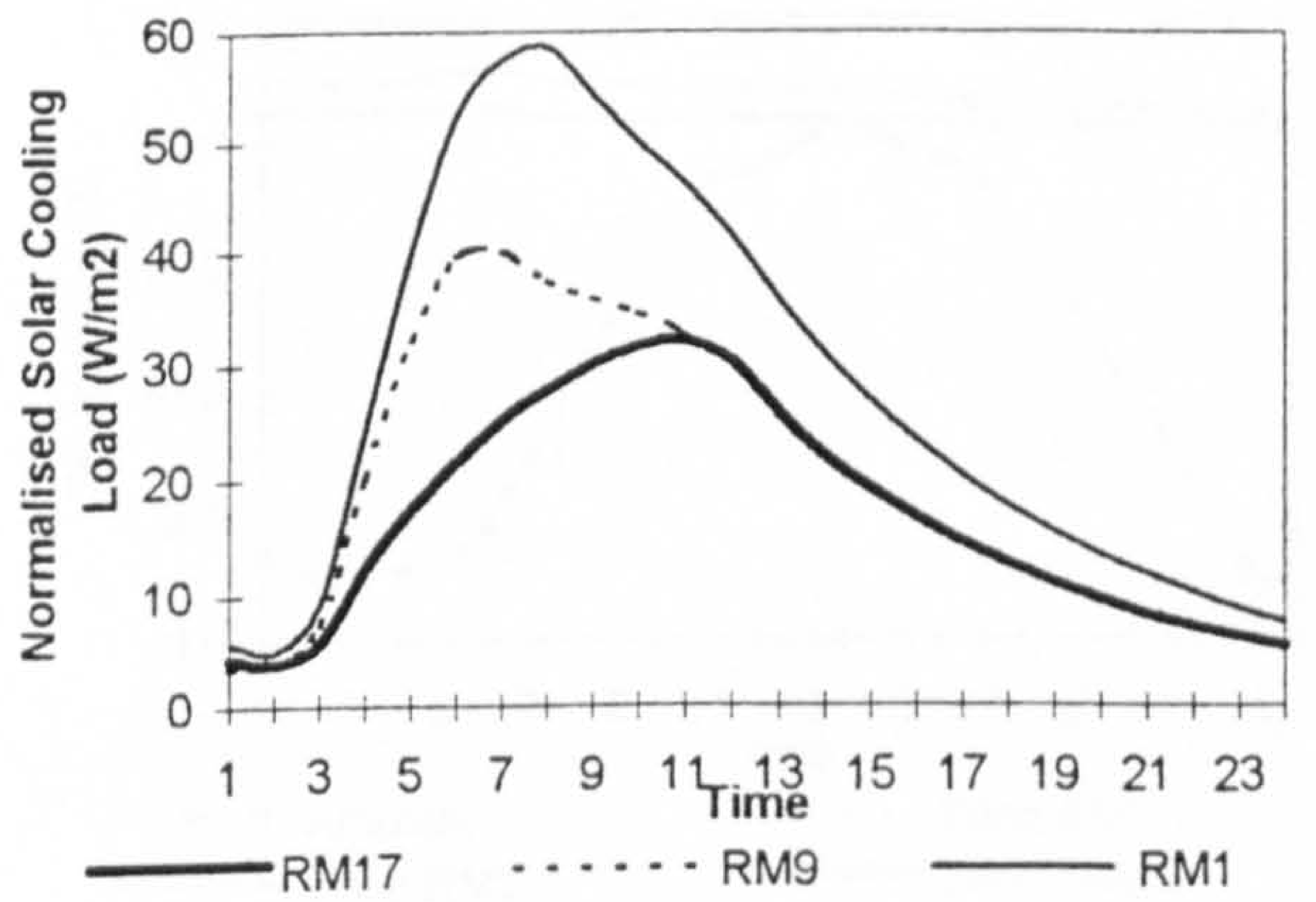


Figure 4.5.1j: Business Hotel Cooling Load due to Solar Gains in July

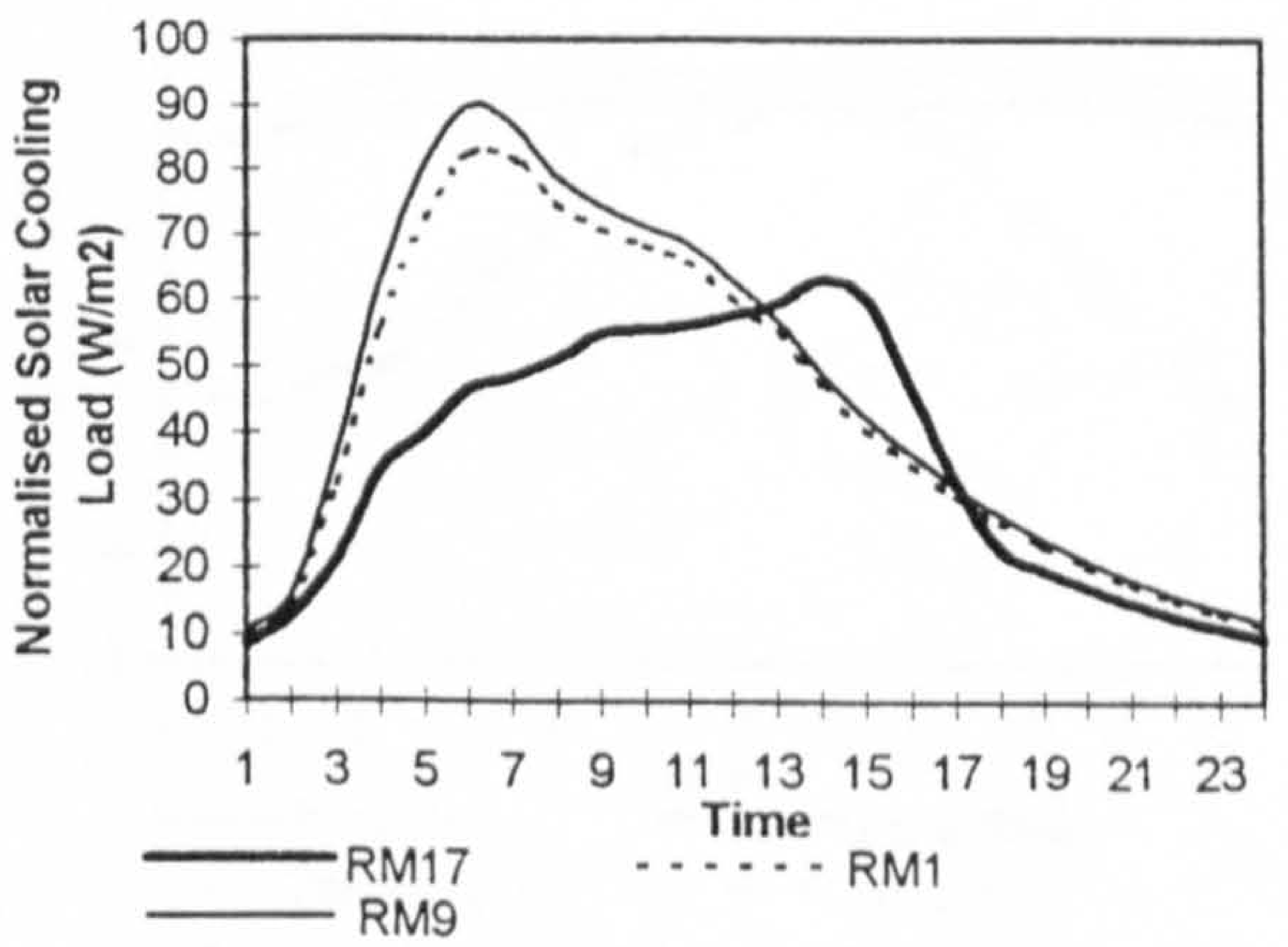


Figure . 4.5.1k: Business Hotel Cooling Load due to Solar Gains in October

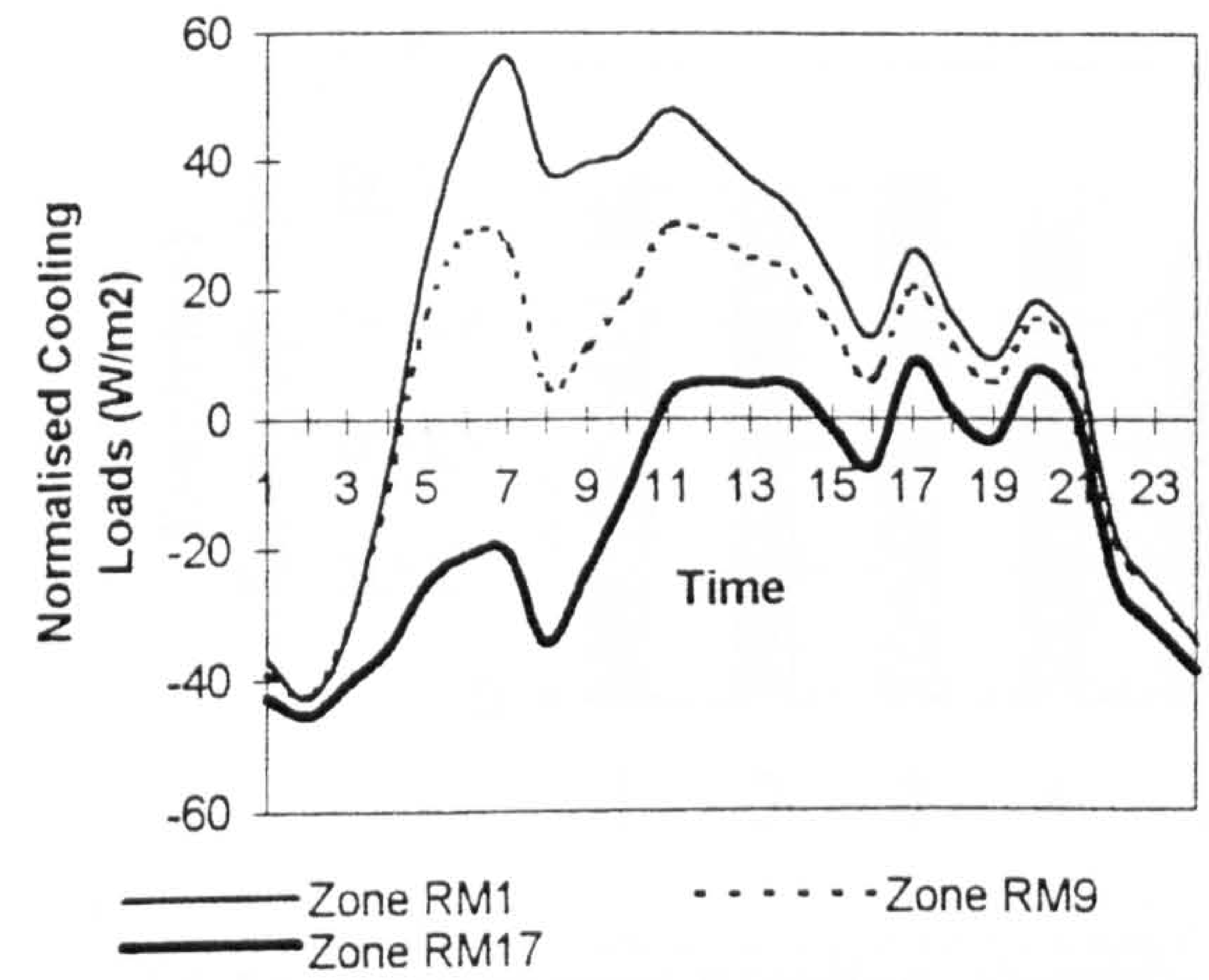


Figure 4.5.1l: Business Hotel Zone Cooling Load in July

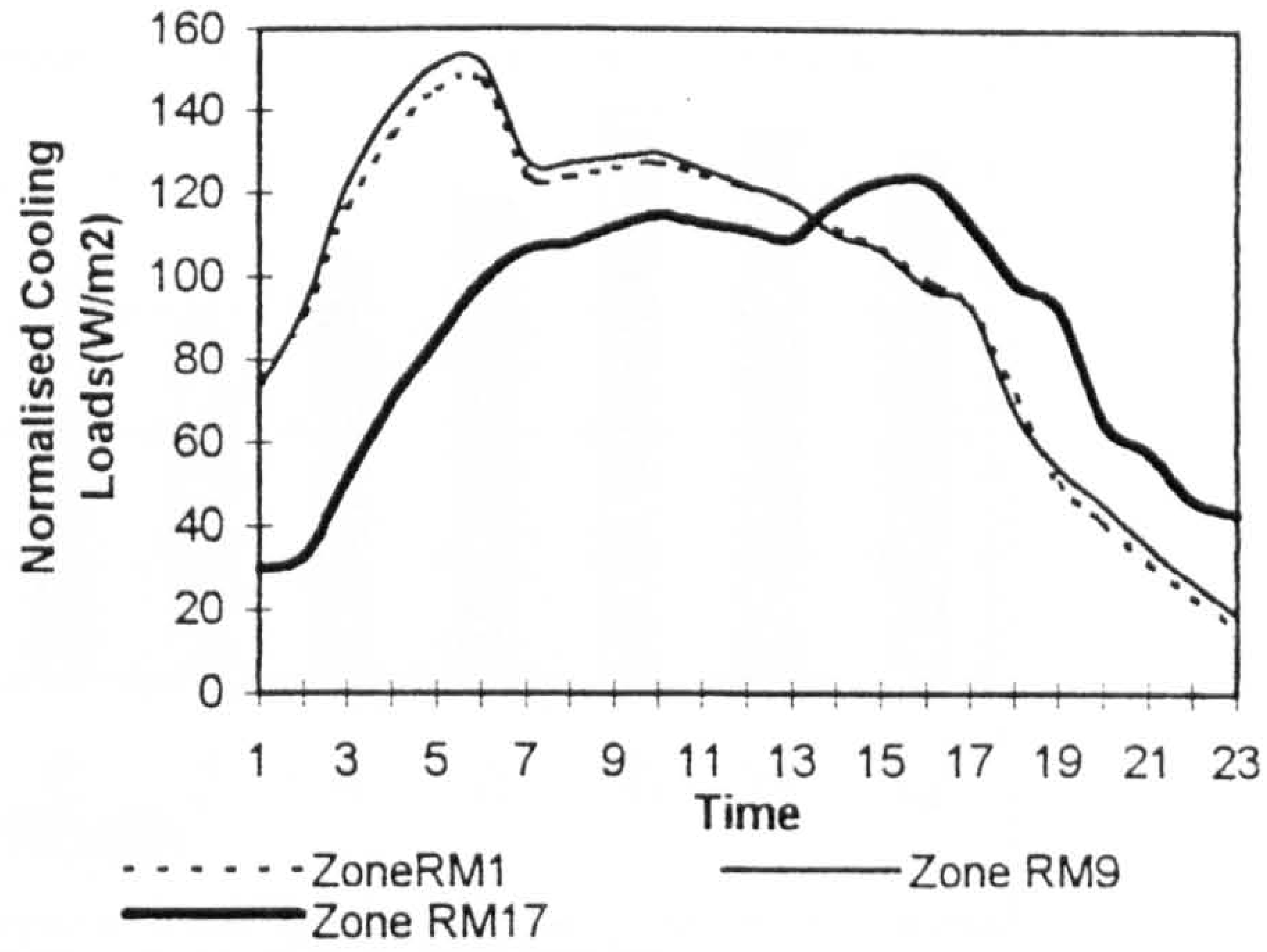


Figure 4.5.1m: Business Hotel Zone Cooling Load in October

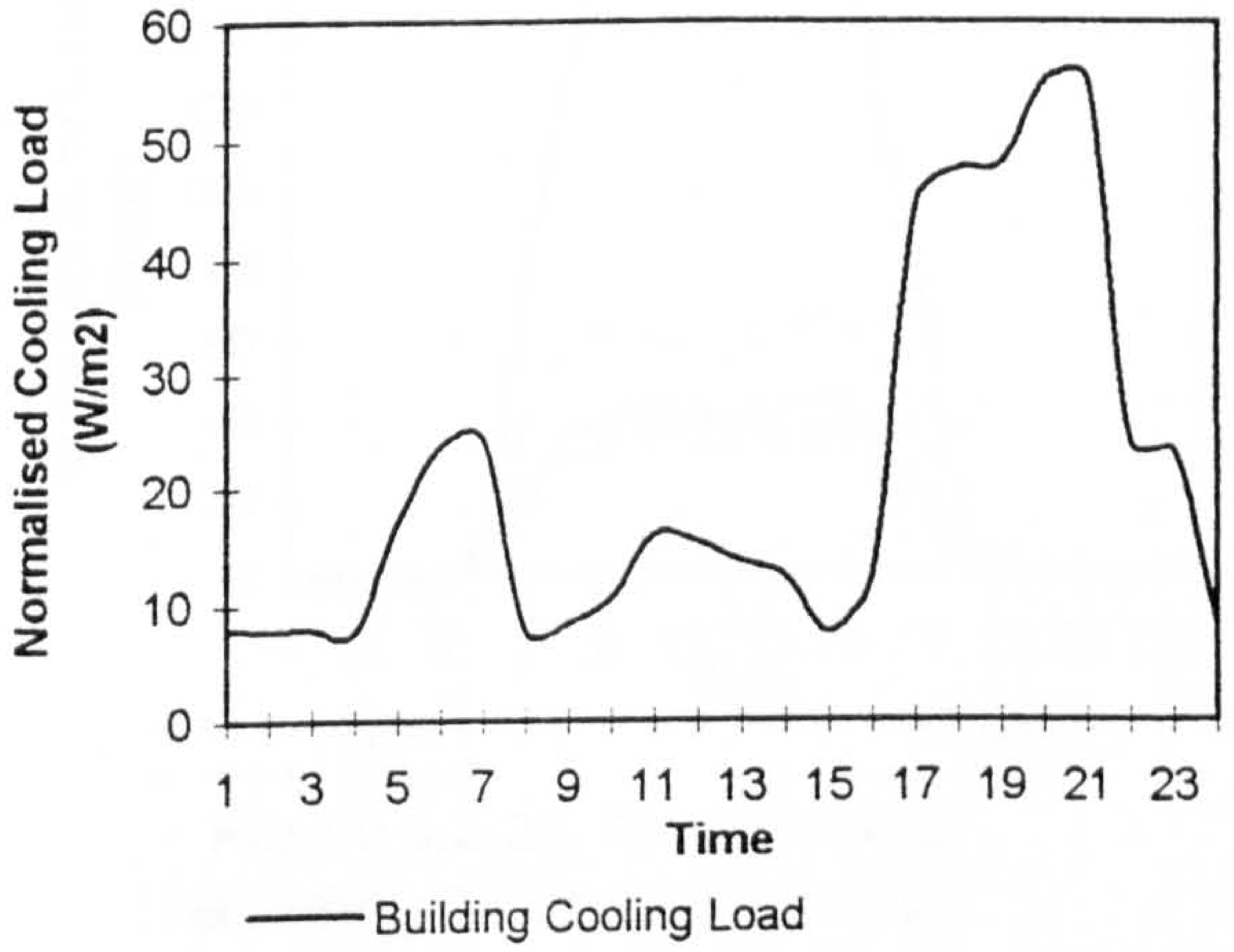


Figure 4.5.1n: Business Hotel: Whole Building Cooling Load in July

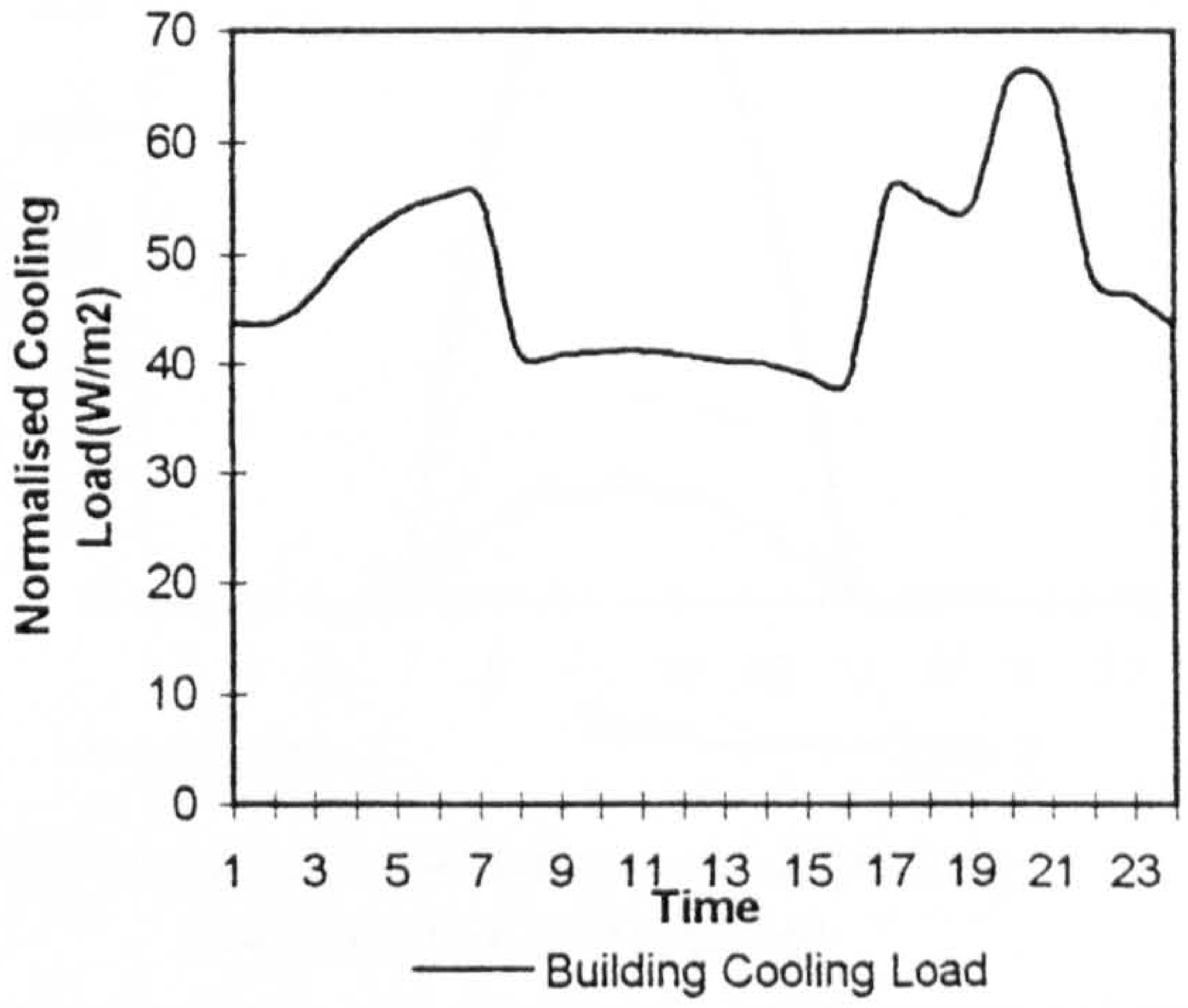


Figure 4.5.1o: Business Hotel: Whole Building Cooling Load in October

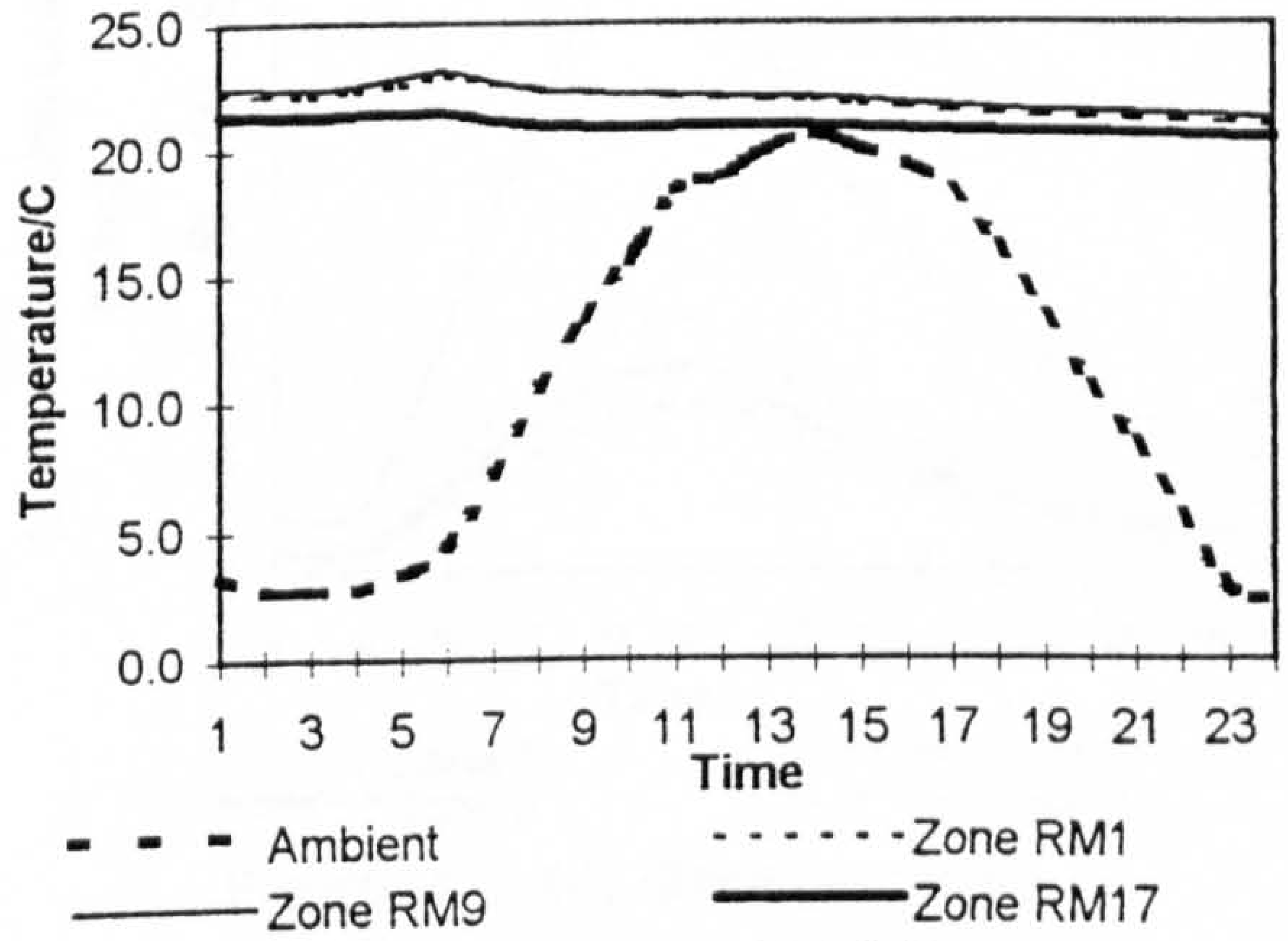


Figure 4.5.1p: Business Hotel: Zone Temperatures in July

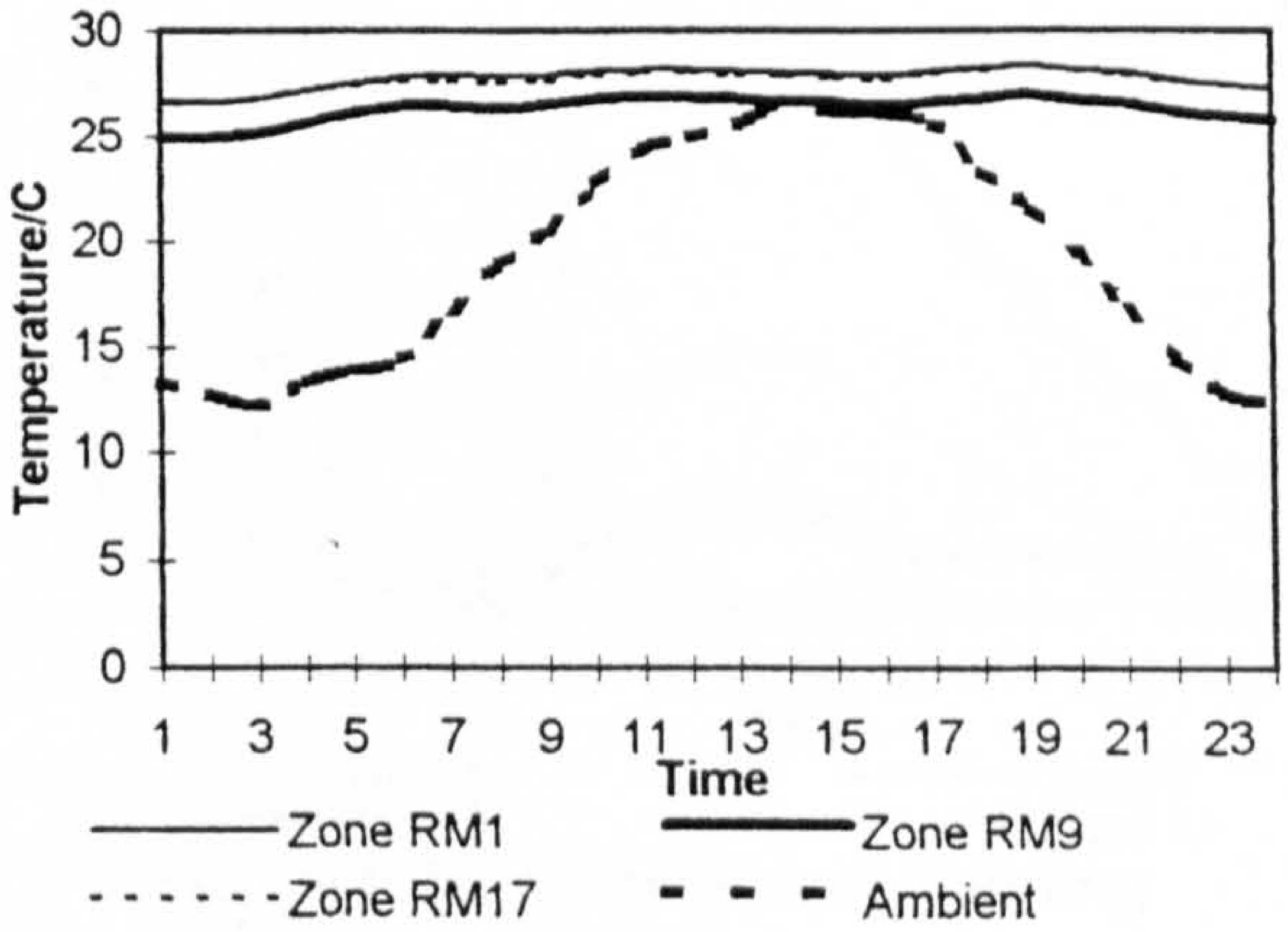


Figure 4.5.1q: Business Hotel: Zone Temperatures in October

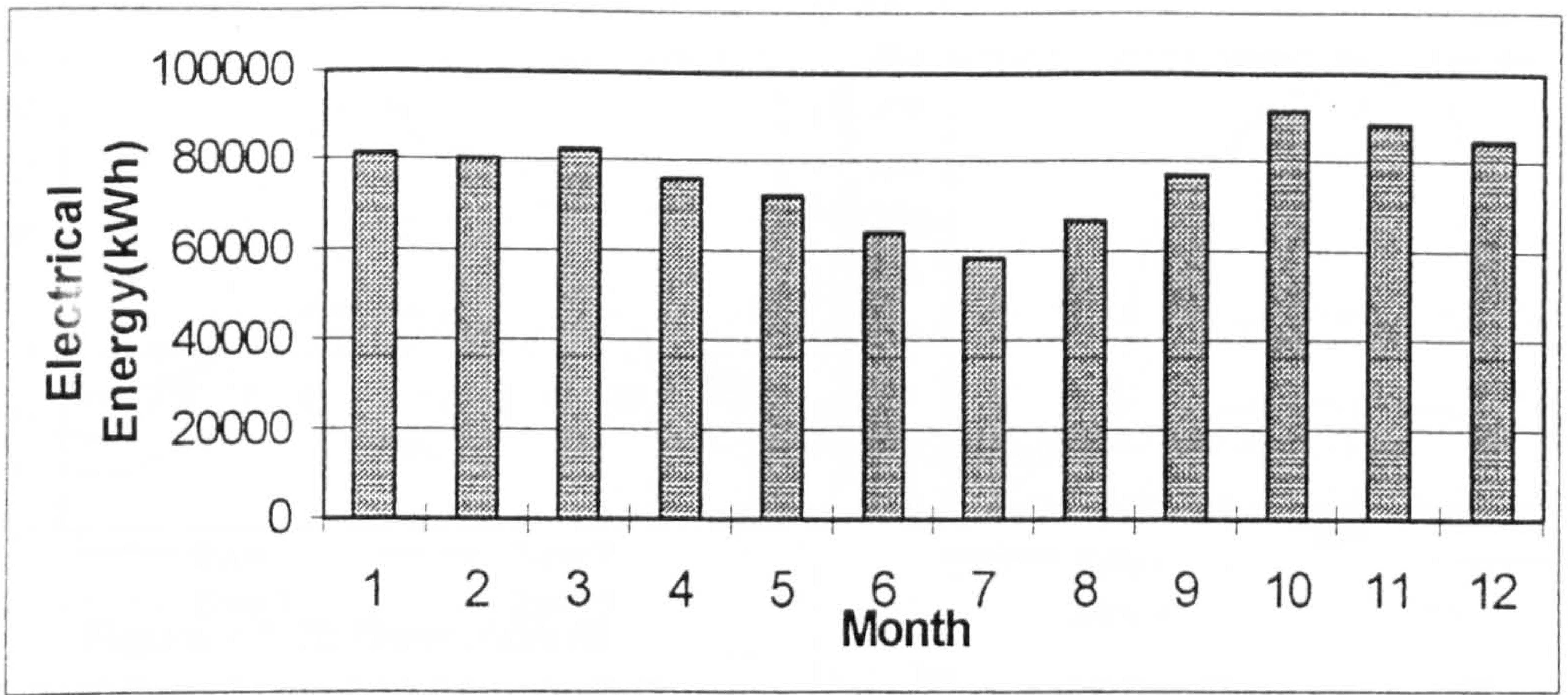


Figure 4.5.2a. Government Building Monthly Electrical Energy Demand

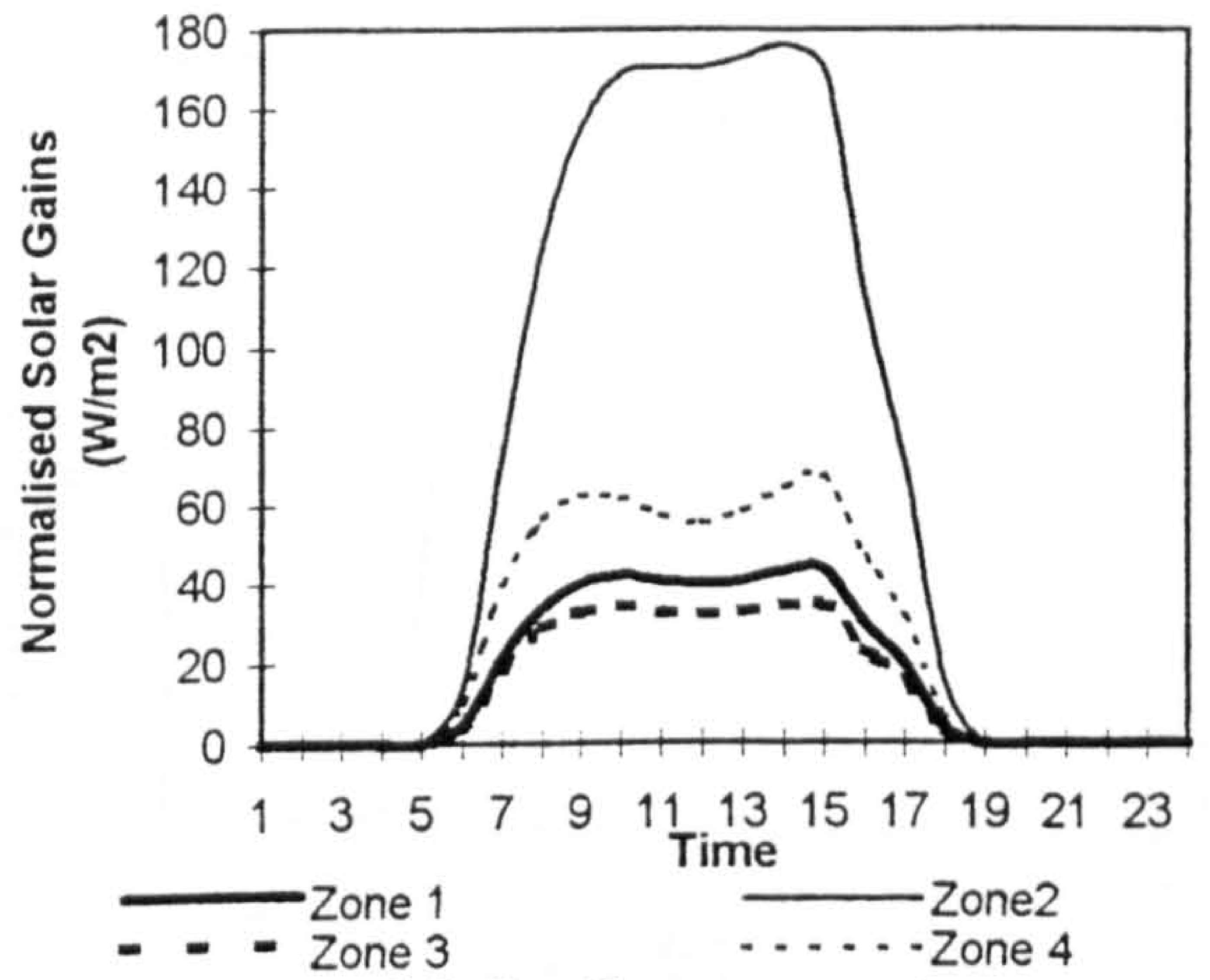


Figure 4.5.2b: Government Building Solar Gains in July

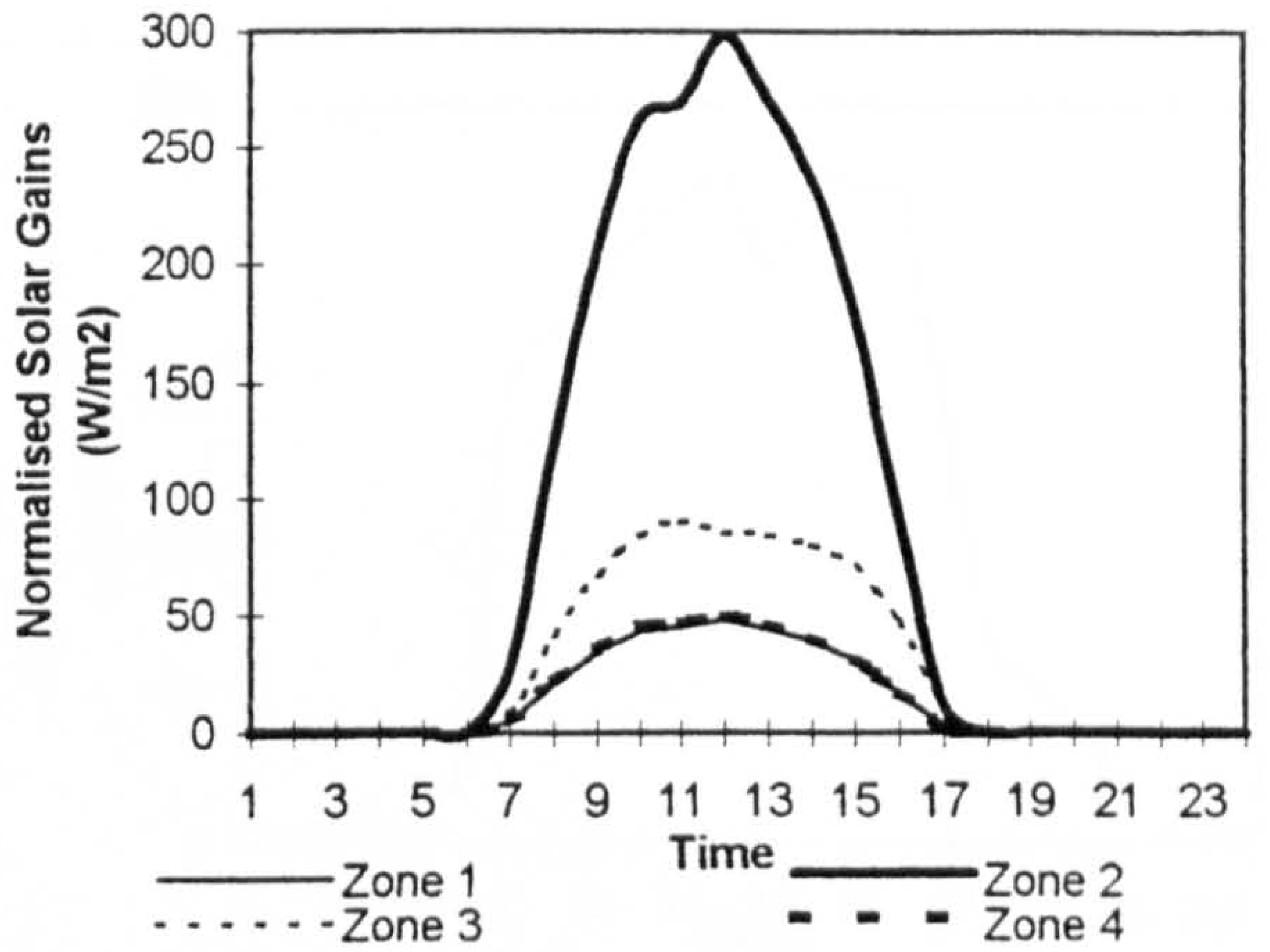


Figure 4.5.2c: Government Building Solar Gains in October

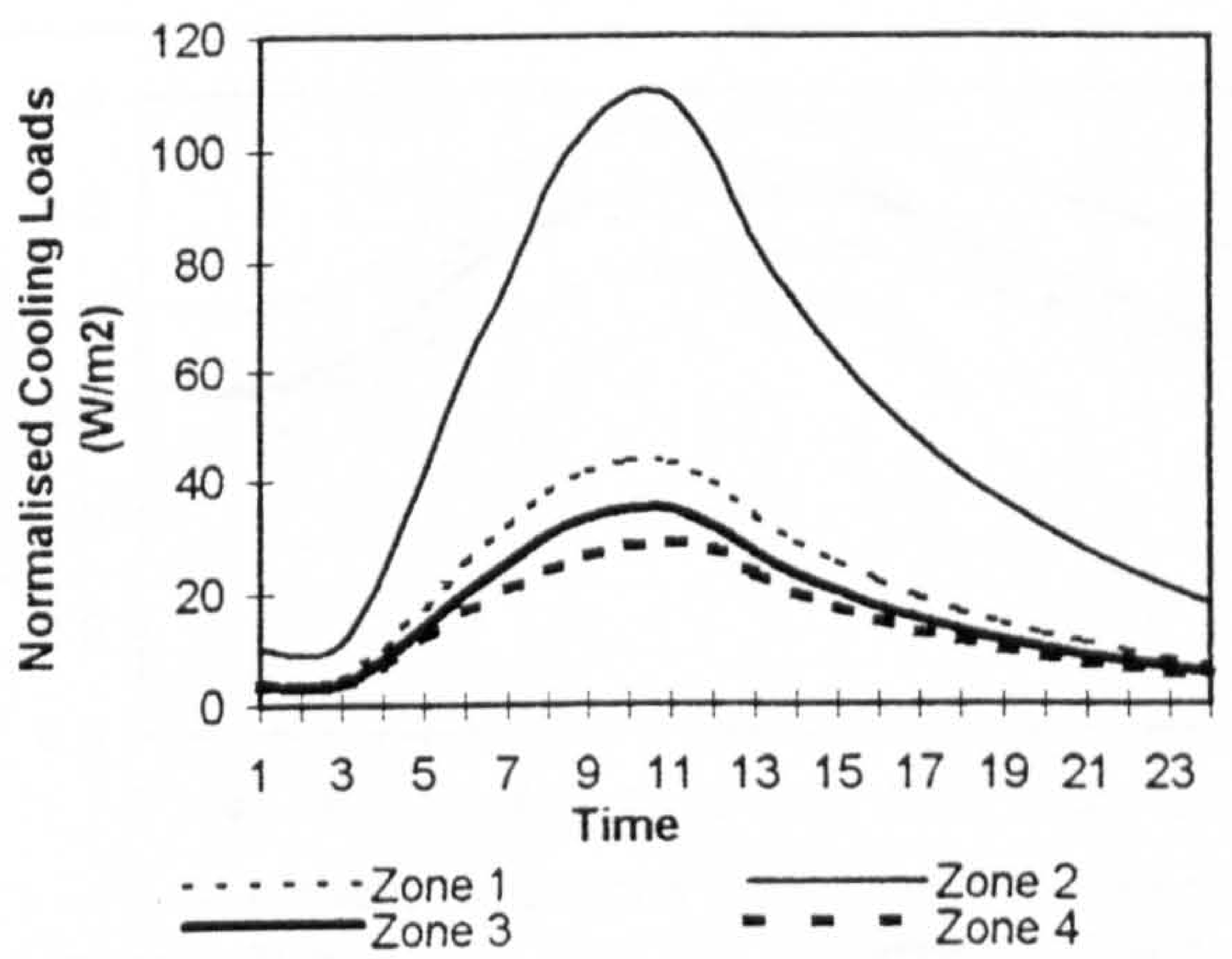


Figure 4.5.2d: Government Building Zone Cooling Loads du to Solar Gains in July

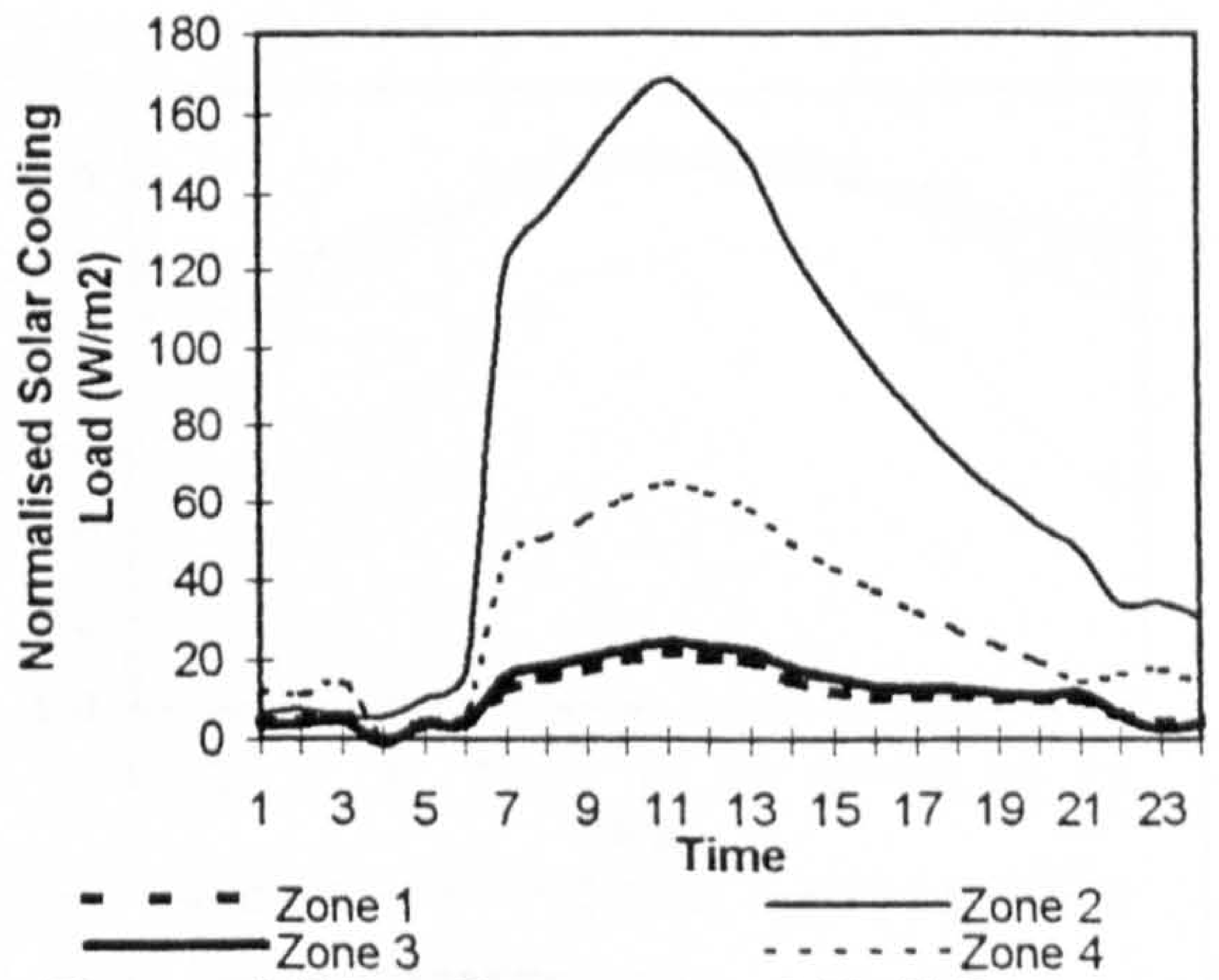


Figure 4.5.2e: Government Building Zone Cooling Loads due to Solar Gains in October

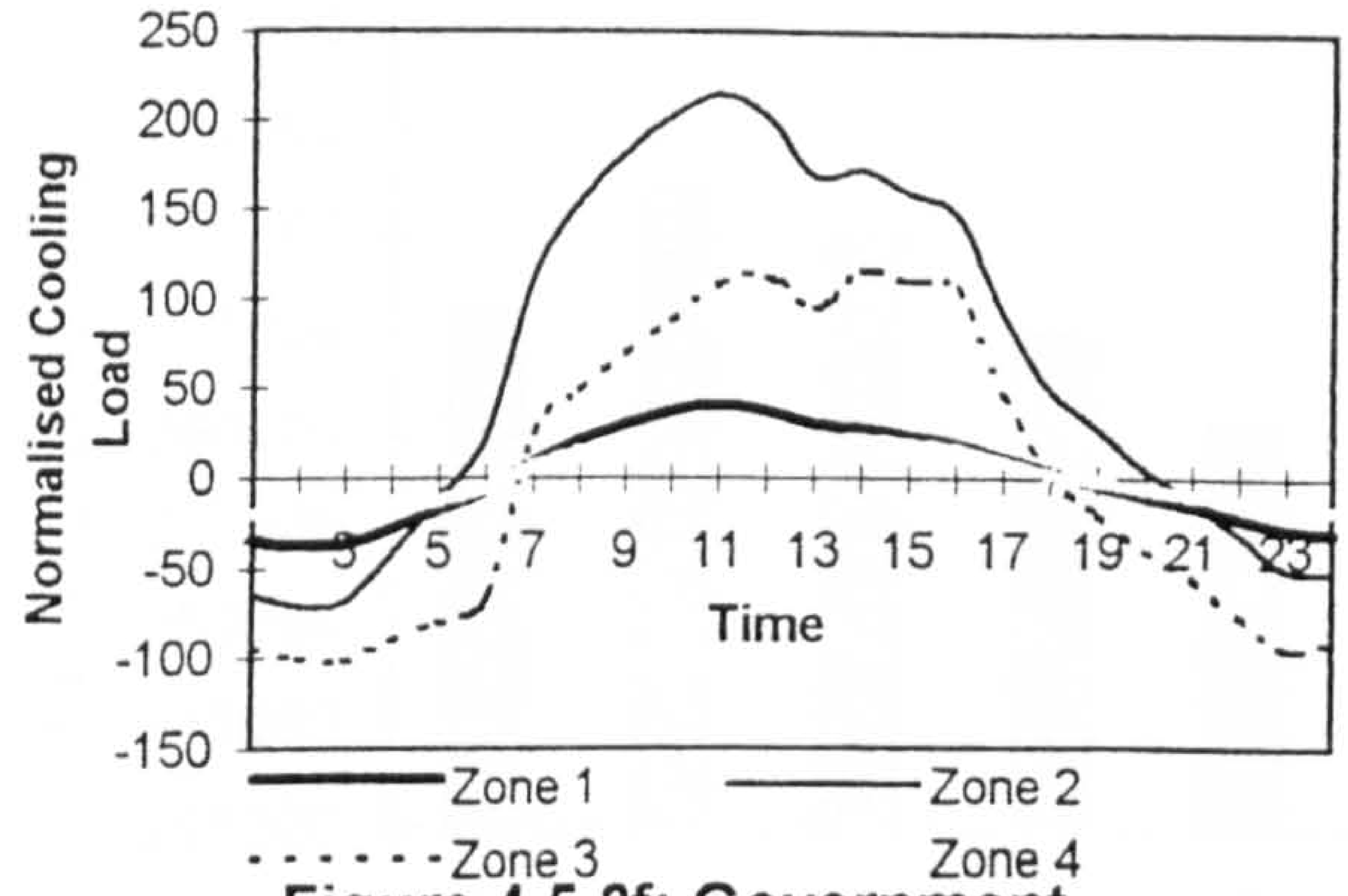


Figure 4.5.2f: Government Building: Zone Cooling Load in July

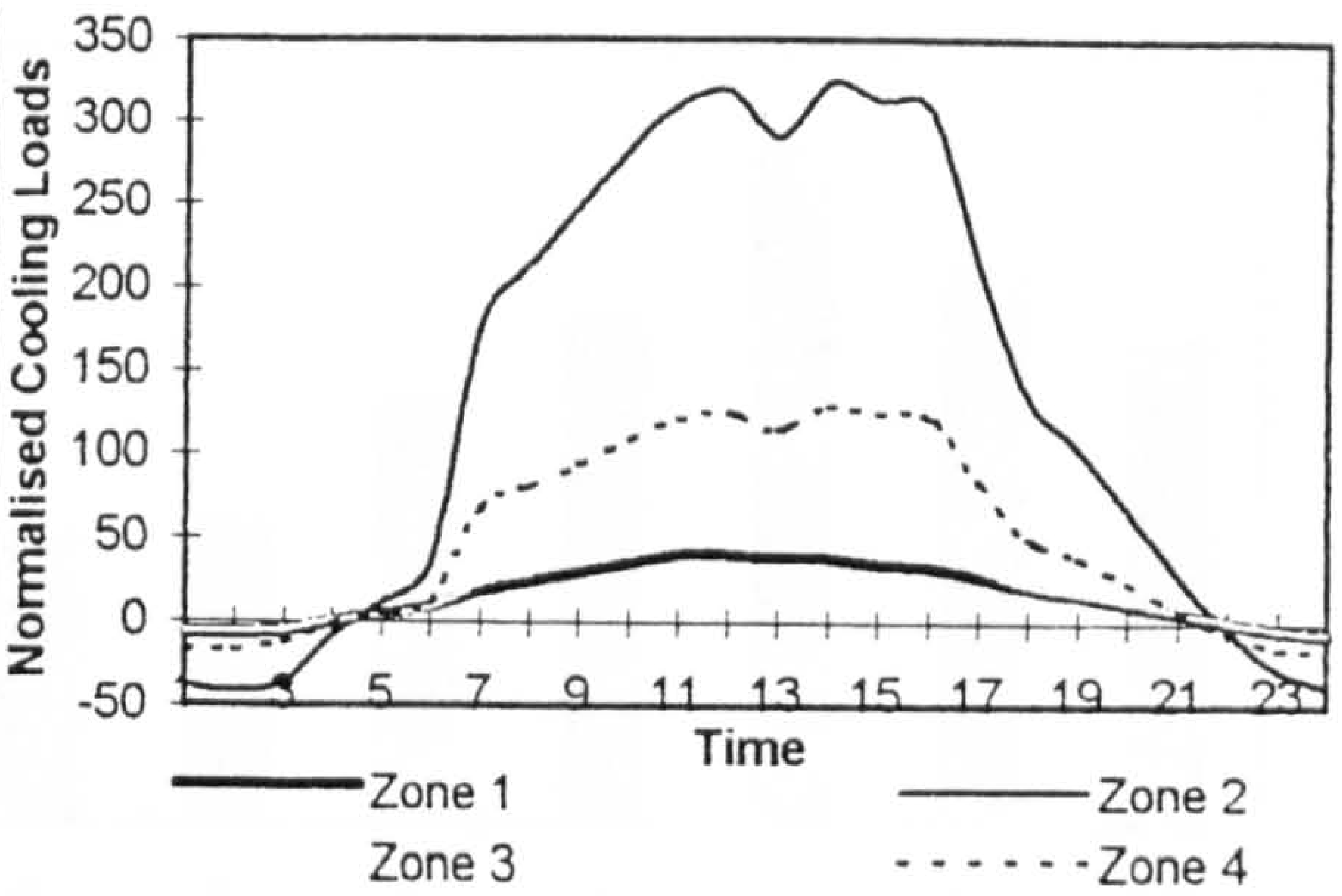


Figure 4.5.2g: Government Building Zone Cooling Loads in October

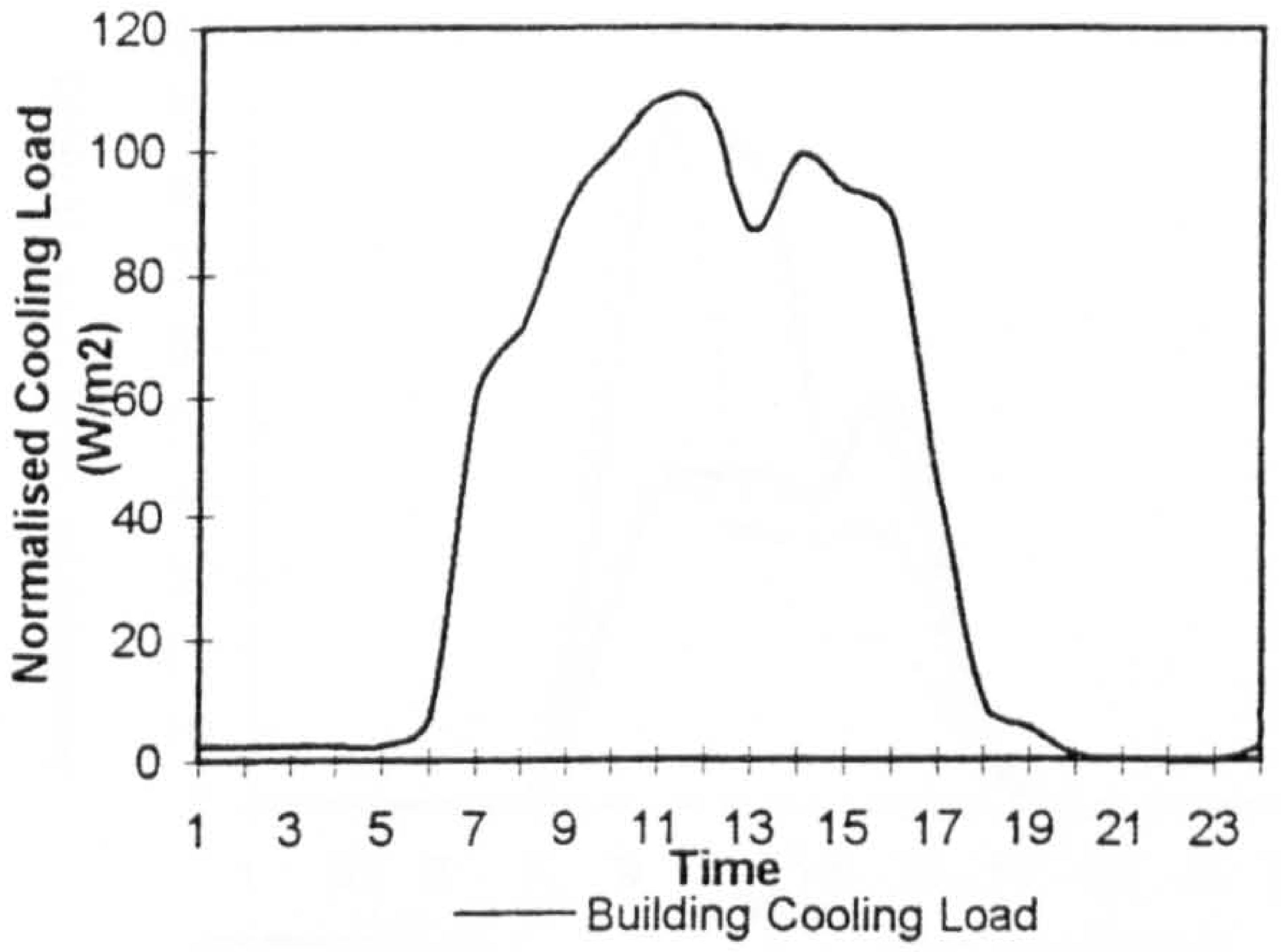


Figure 4.5.2h: Government Building: Cooling Load of Whole Building in July

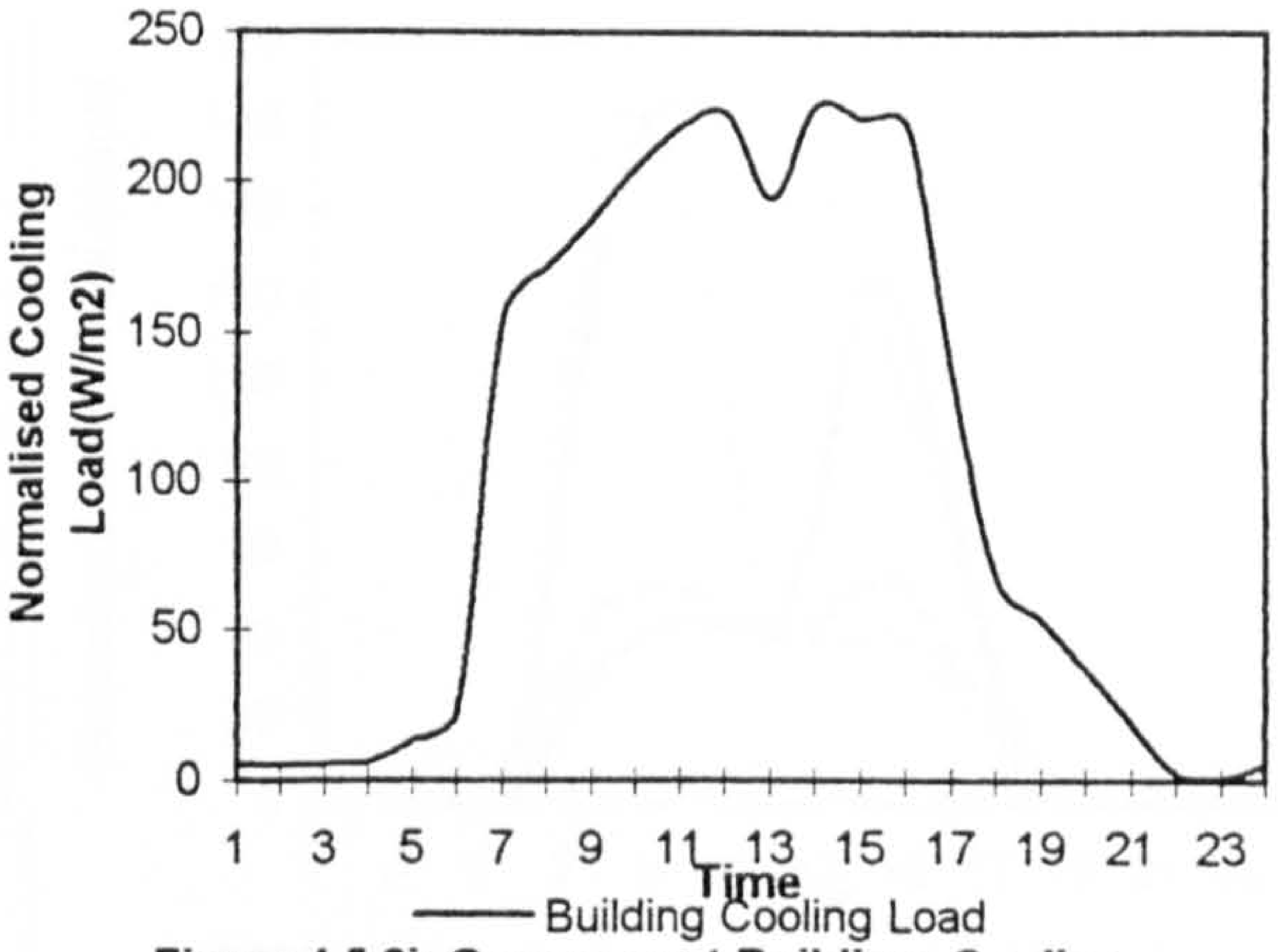


Figure 4.5.2i: Government Building: Cooling Load of Building in October

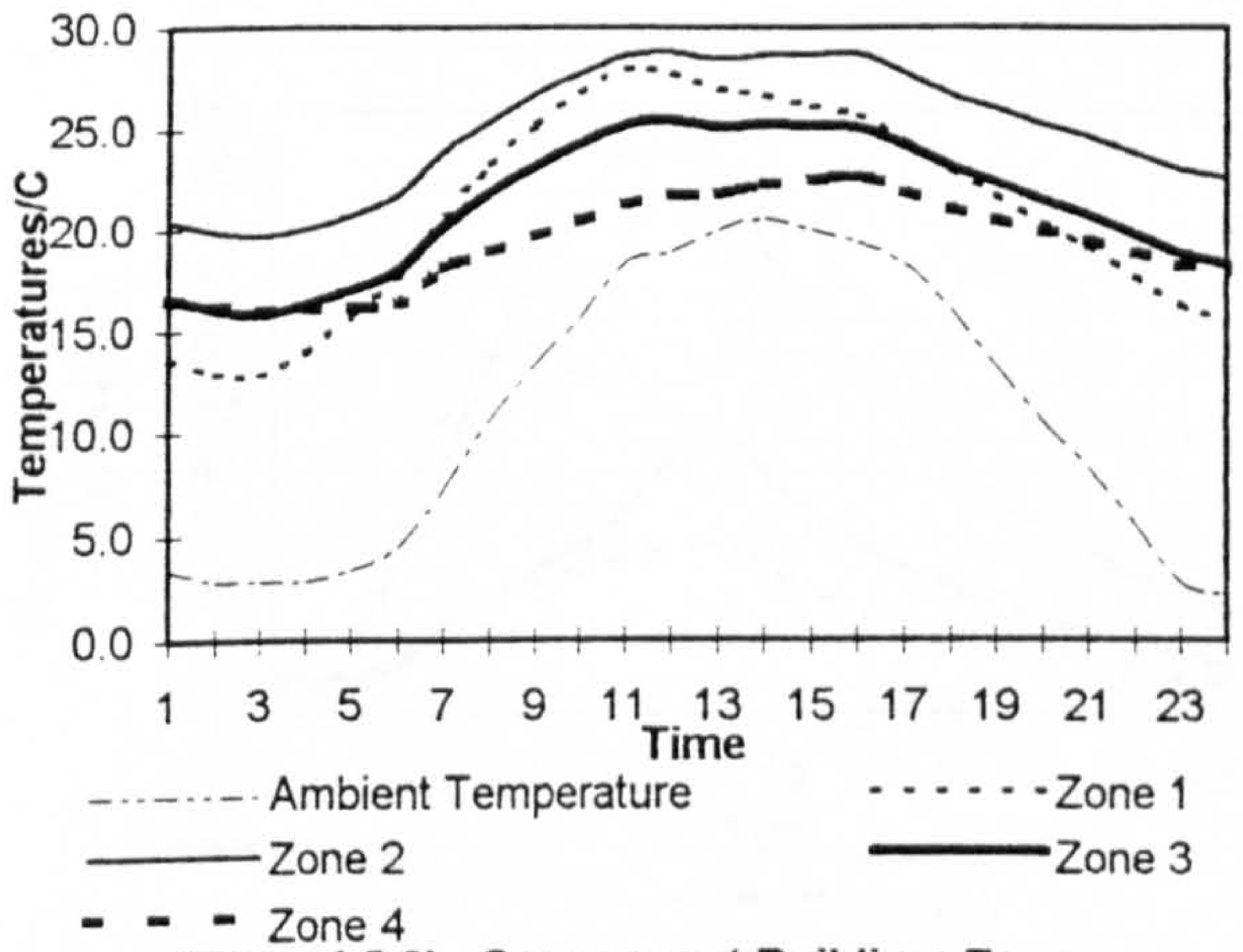


Figure 4.5.2h: Government Building: Zone Temperatures in July

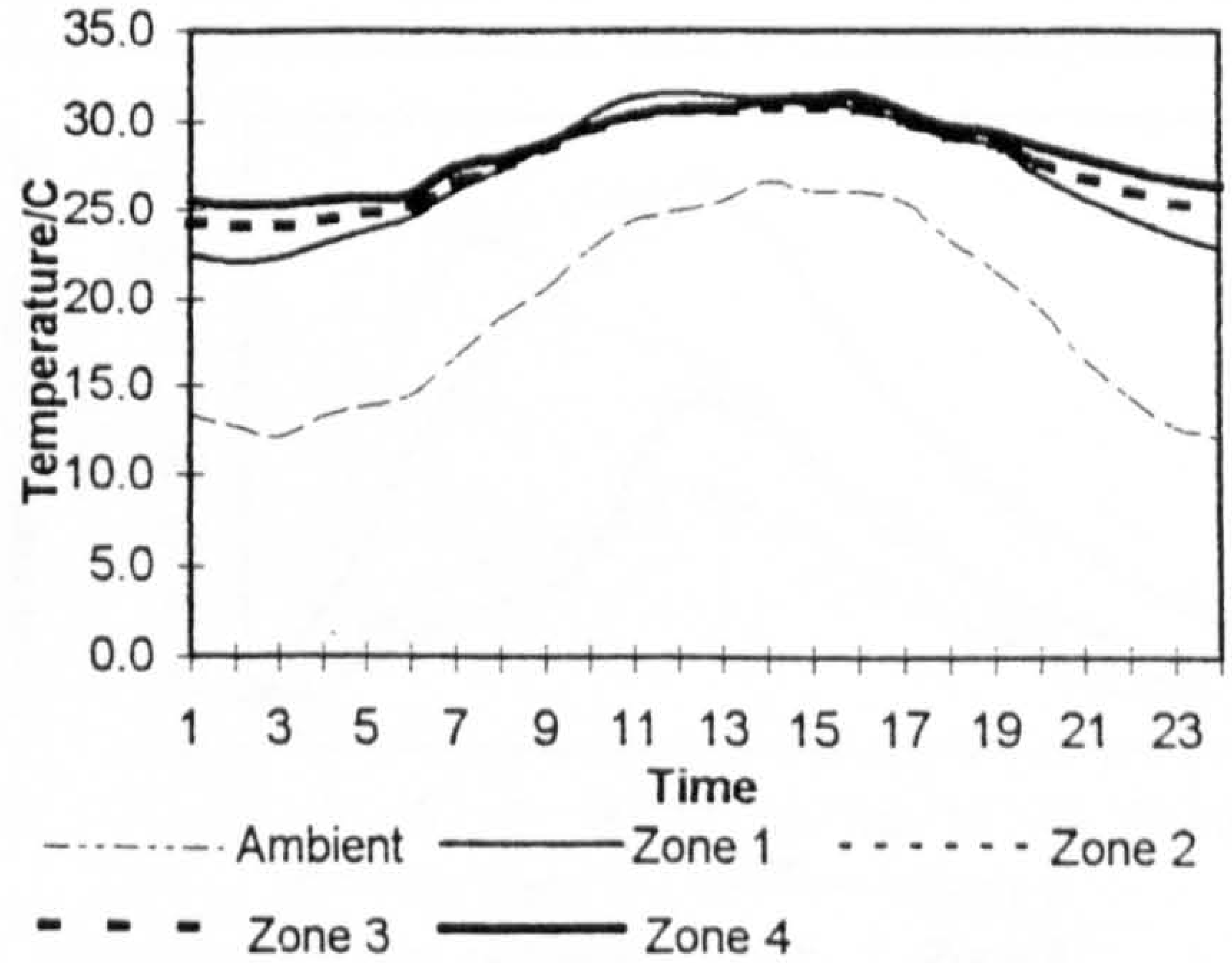


Figure 4.5.2i: Government Building, Zone Temperatures in October

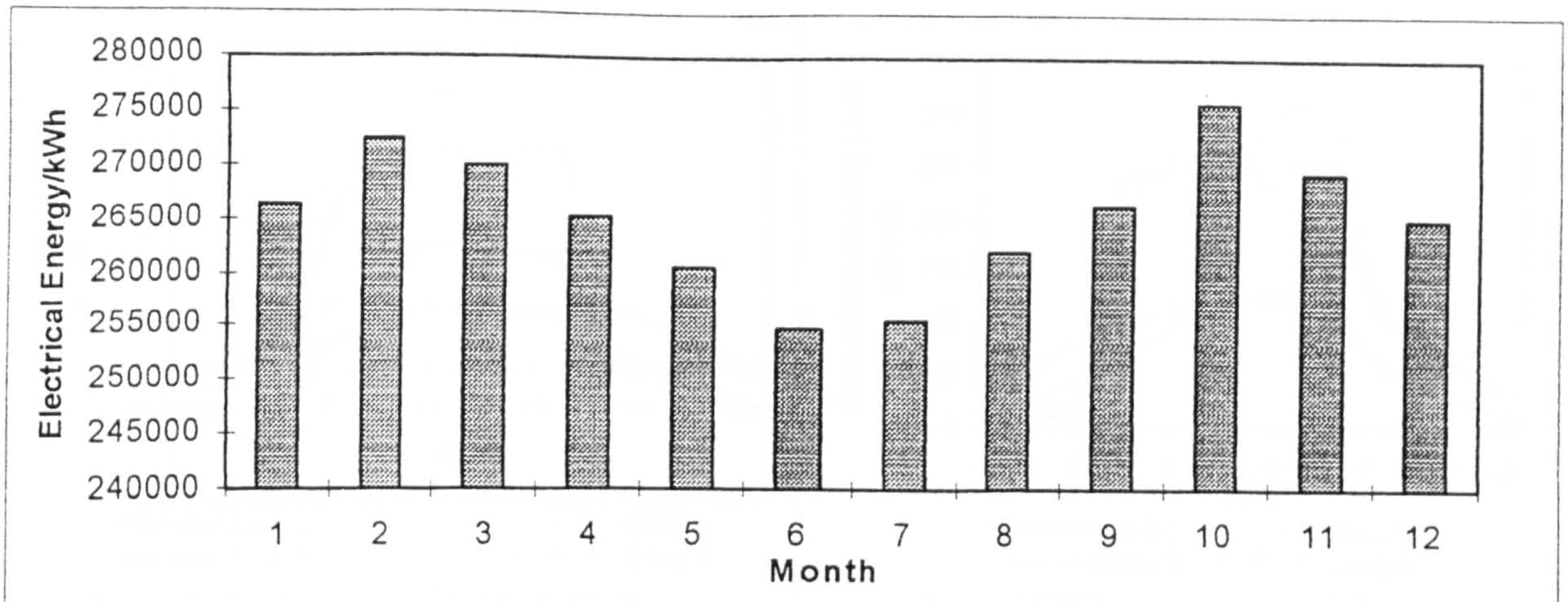


Figure 4.5.3a: Tenant Occupied Building, Monthly Electrical Energy Consumed

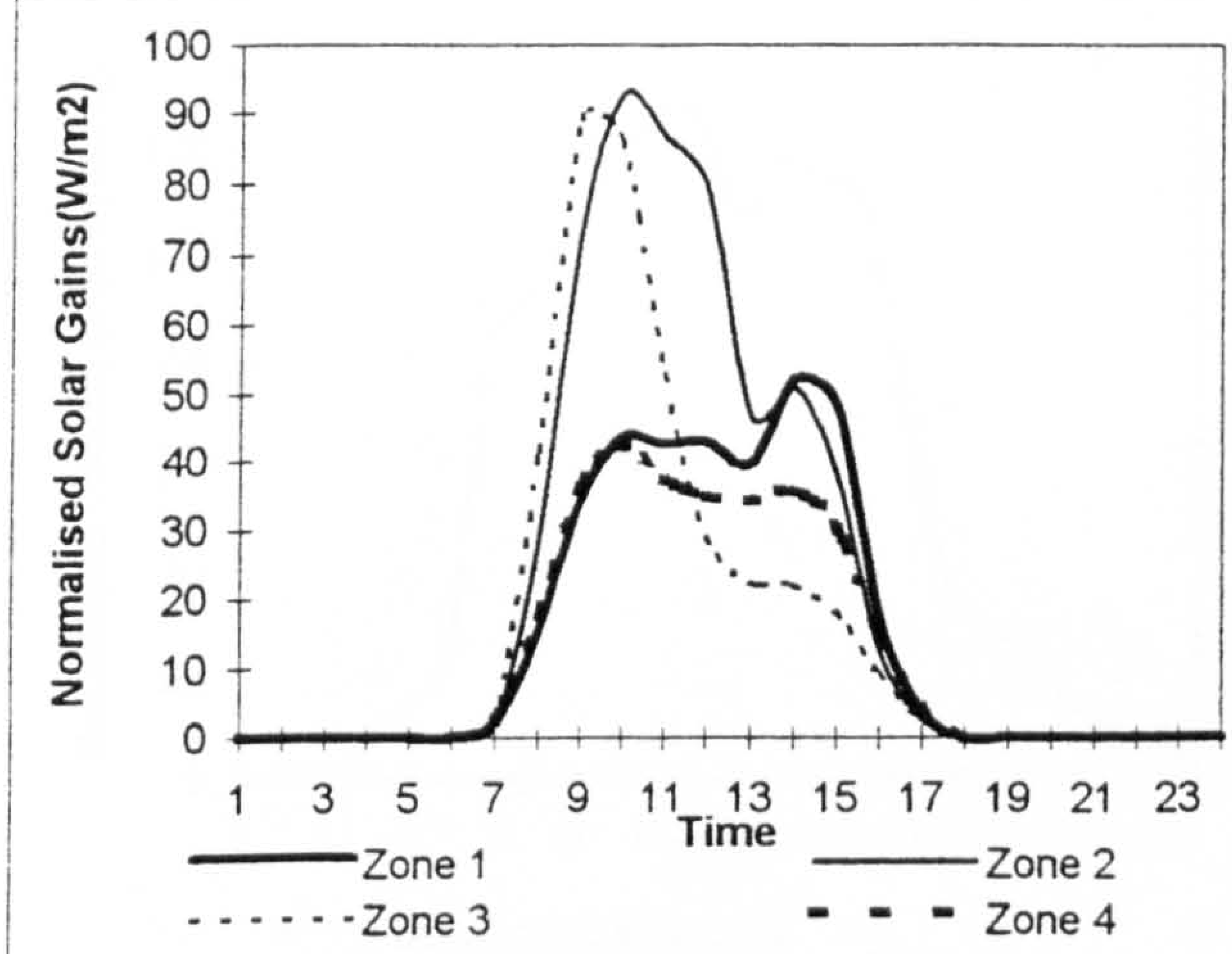


Figure 4.5.3a: Tenant Occupied Building Solar Gains in July

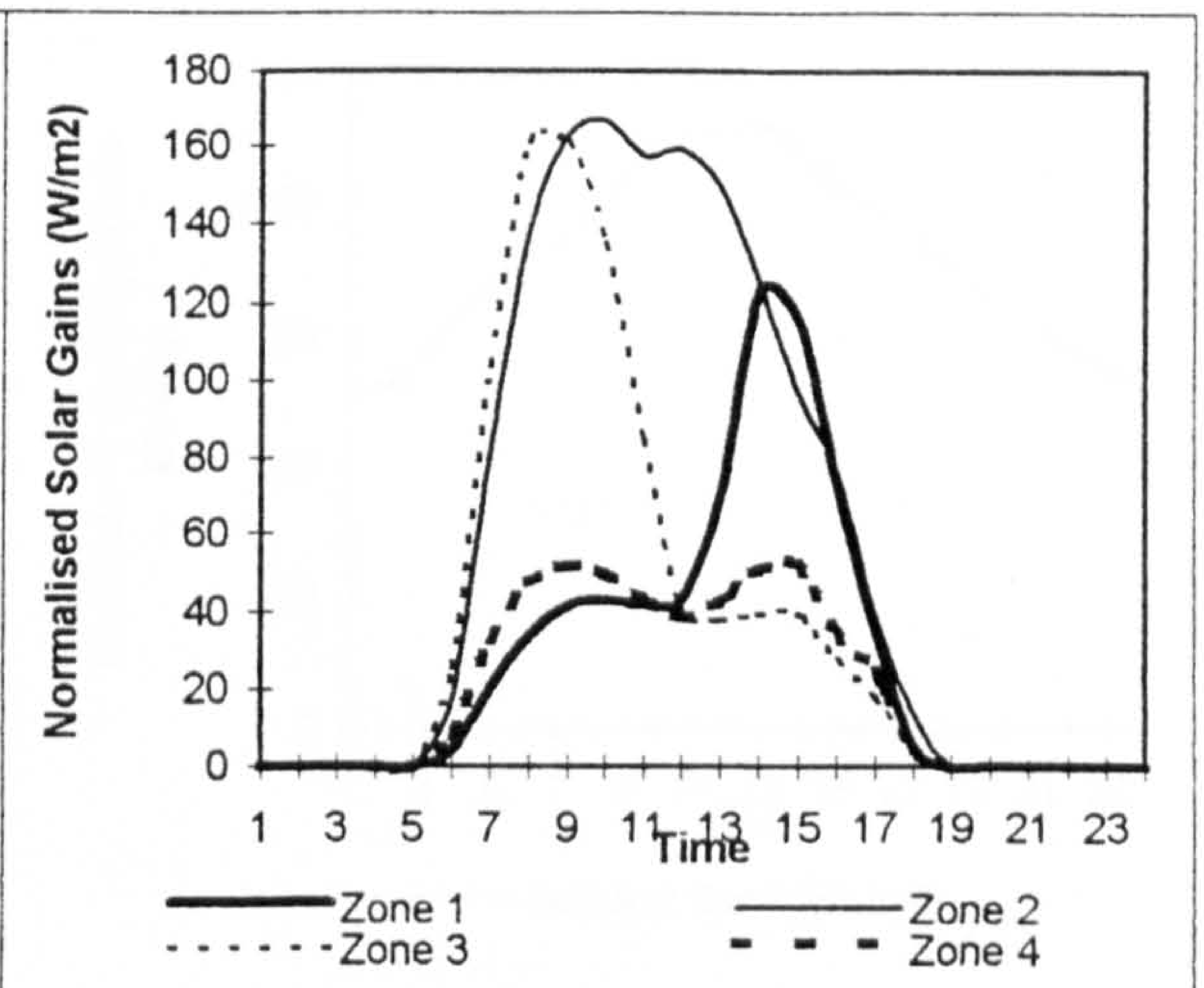


Figure 4.5.3b: Tenant Occupid Building Solar Gains in October

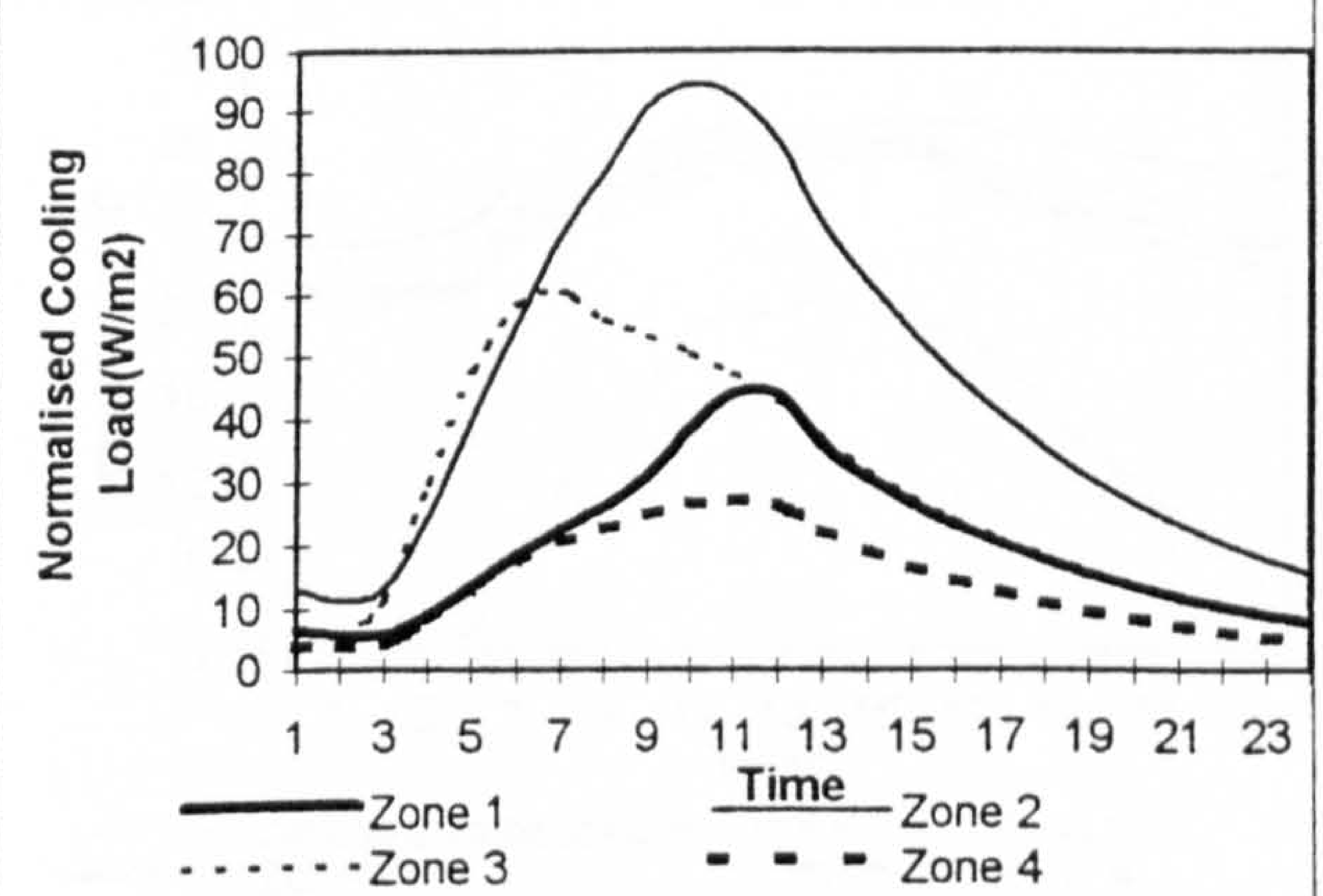


Figure 4.5.3.c: Tenant Occupied Building: Cooling Loads due to Solar Gains in July

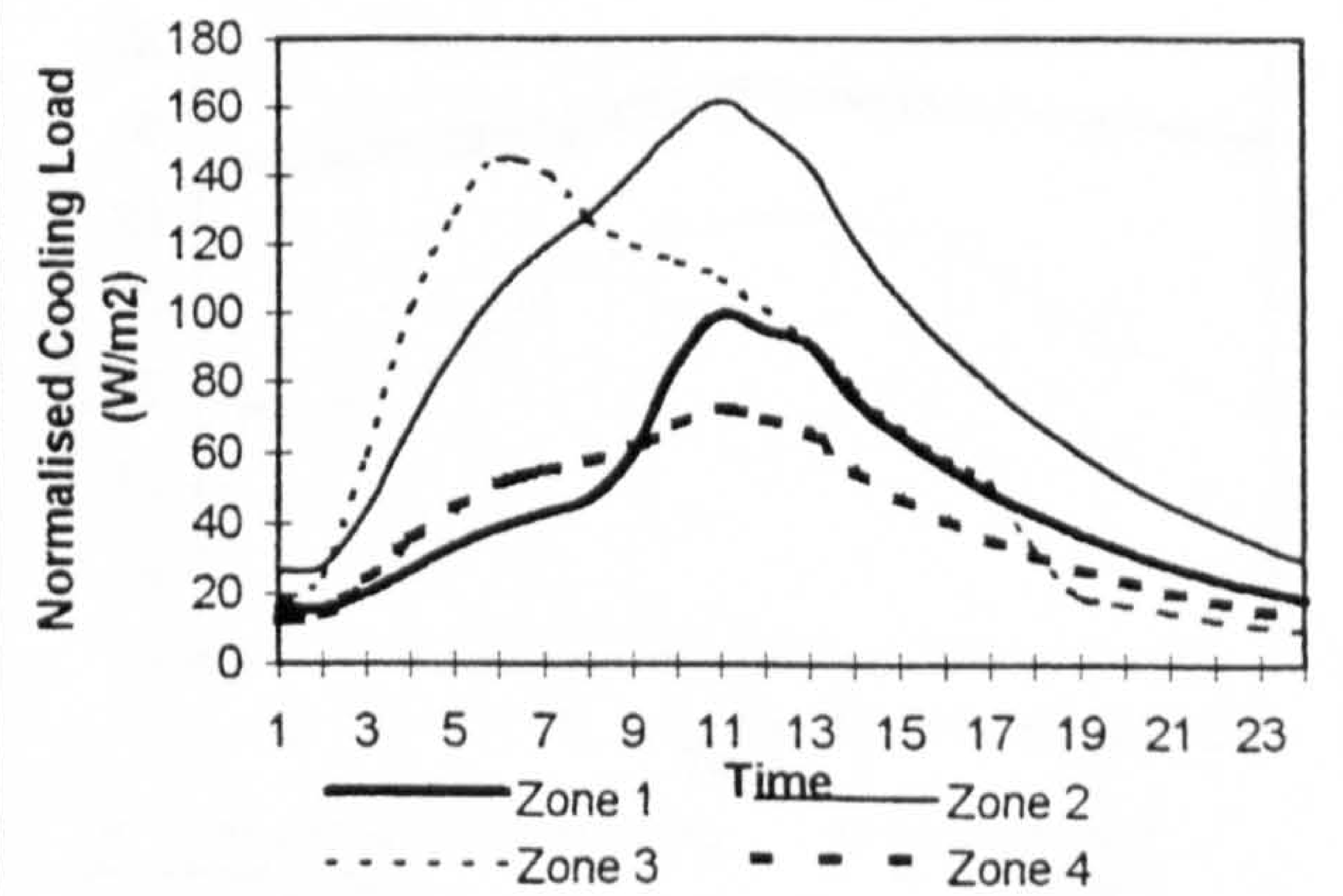


Figure 4.5.3d: Tenant Occupied Building, Cooling Load due to Solar Gains in October

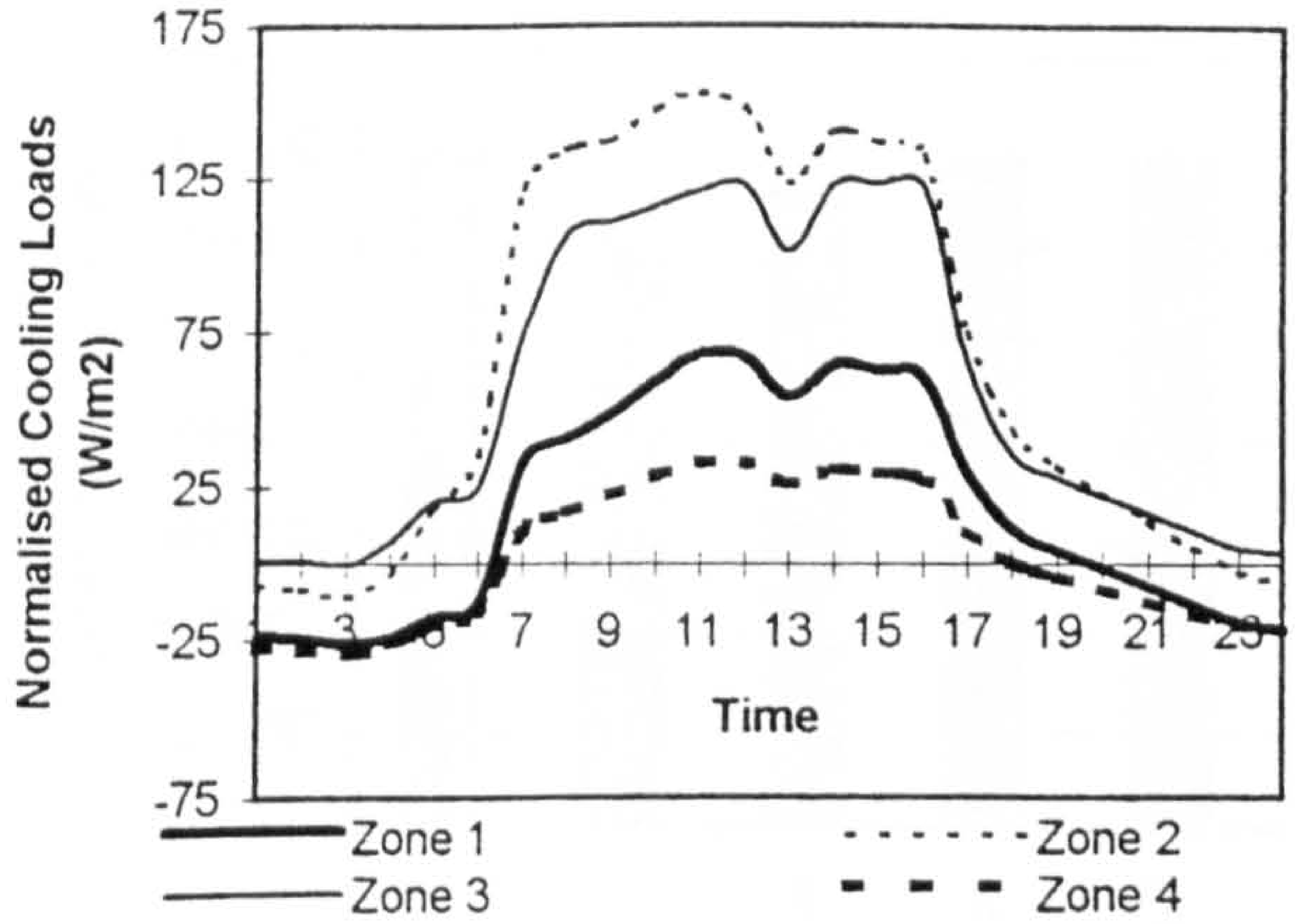


Figure 4.5.3e: Tenant Occupied Building: Zone Cooling Loads in July

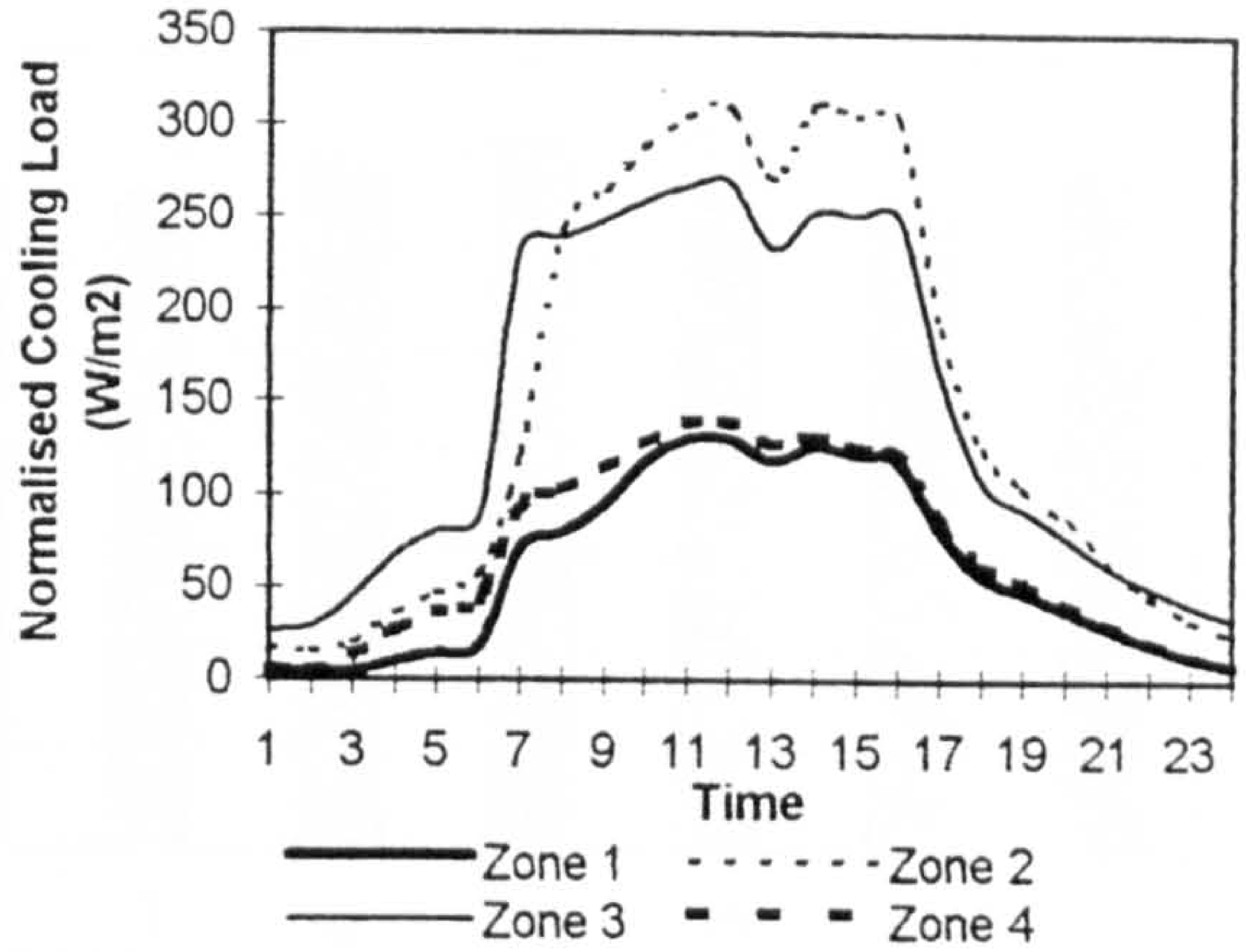


Figure 4.5.3f: Tenant Occupied Building: Zone Cooling Load in October

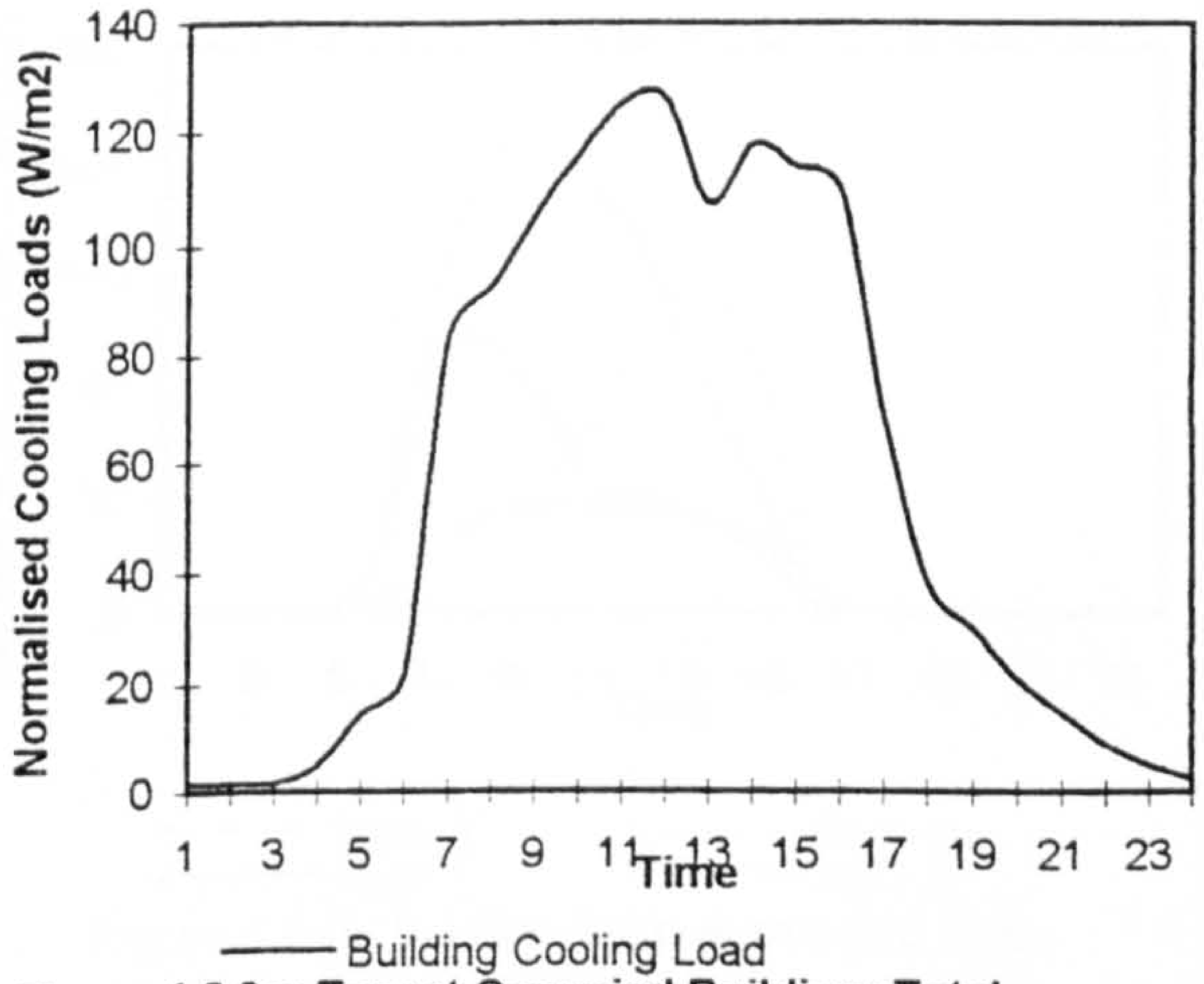


Figure 4.5.3g: Tenant Occupied Building: Total Building Cooling Loads in July

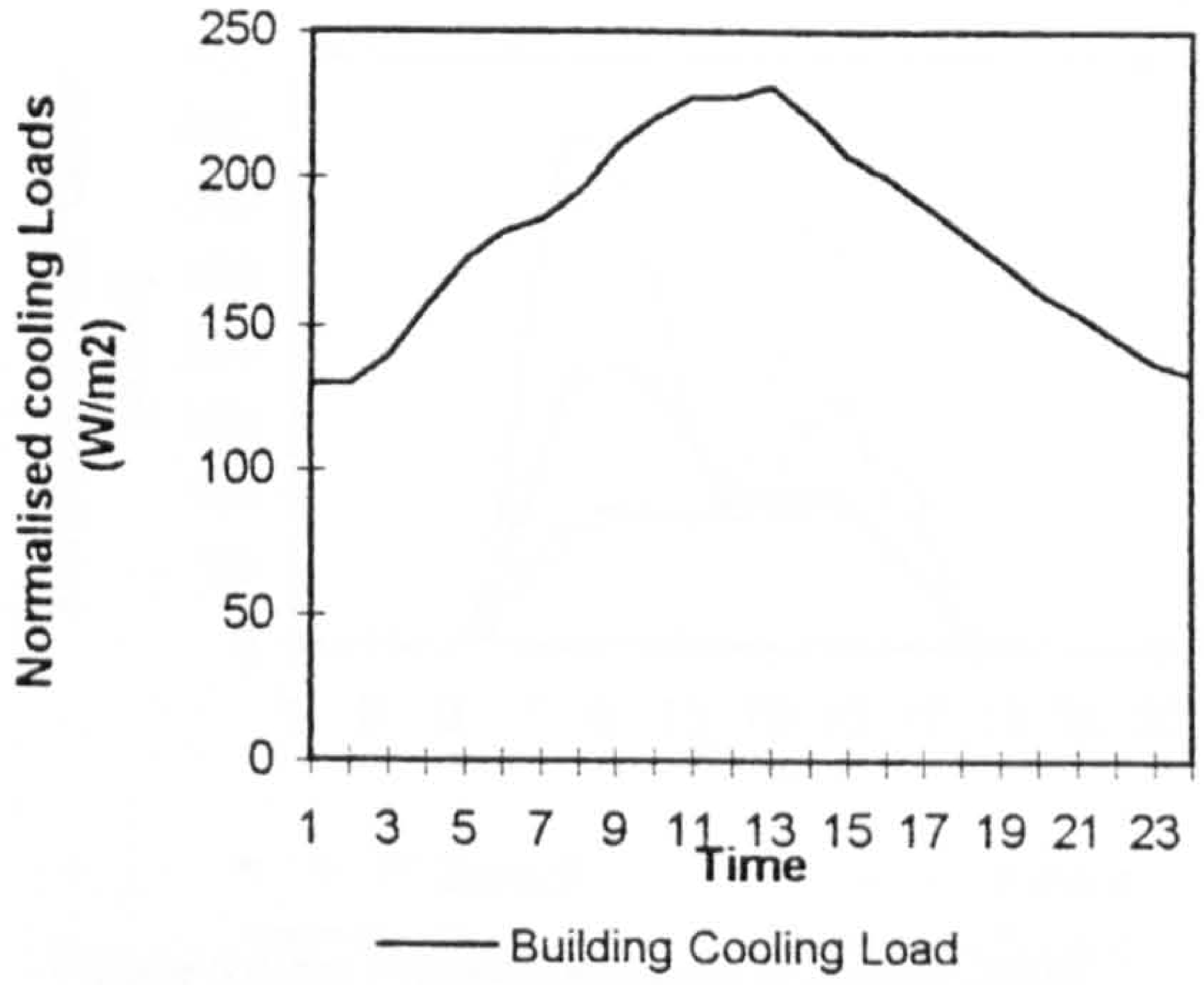


Figure 4.5.3h: Tenant Occupied Building Total Building Cooling Load in October

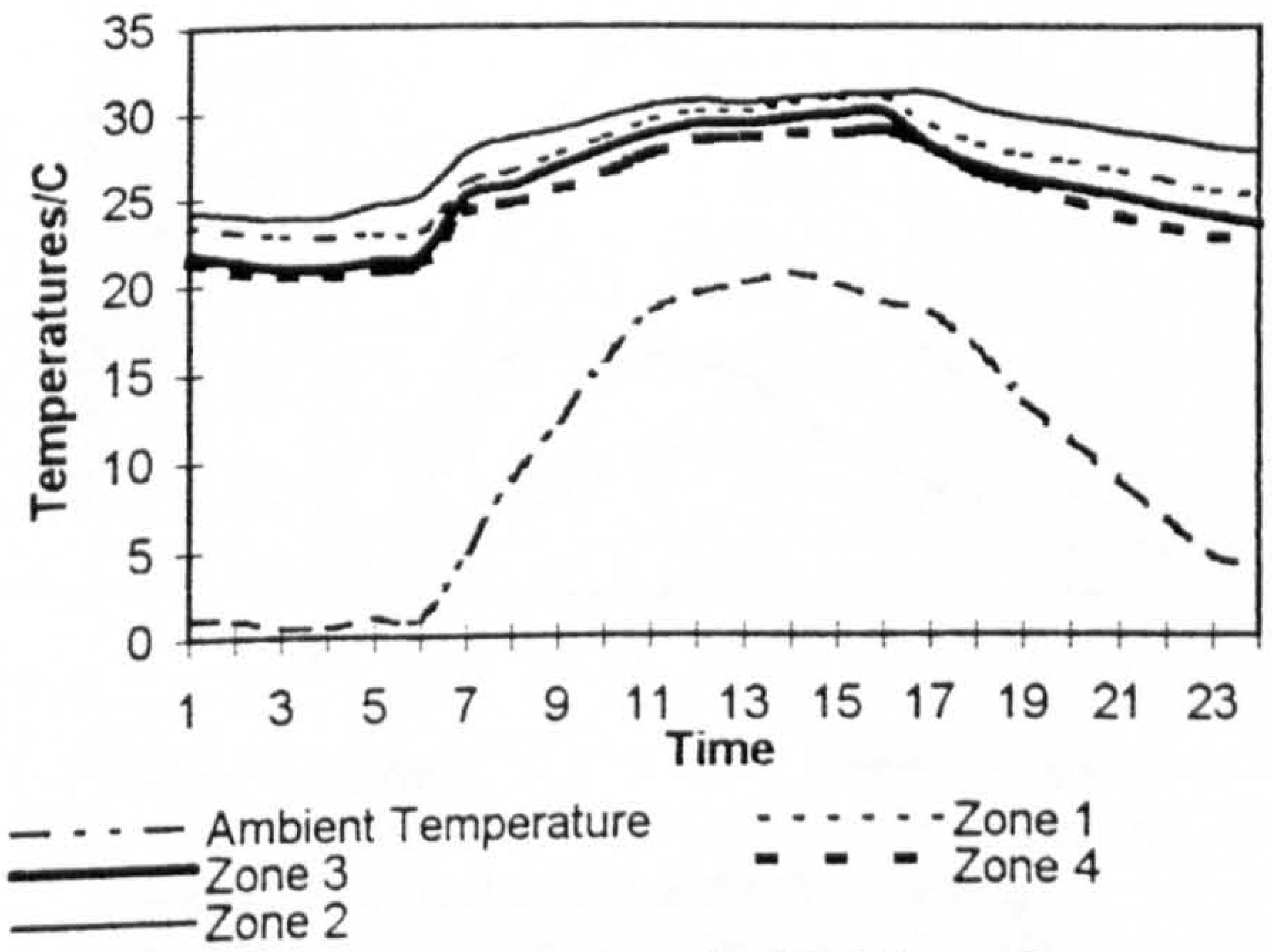


Figure 4.5.3i: Tenant Occupied Building; Zone Temperatures in July

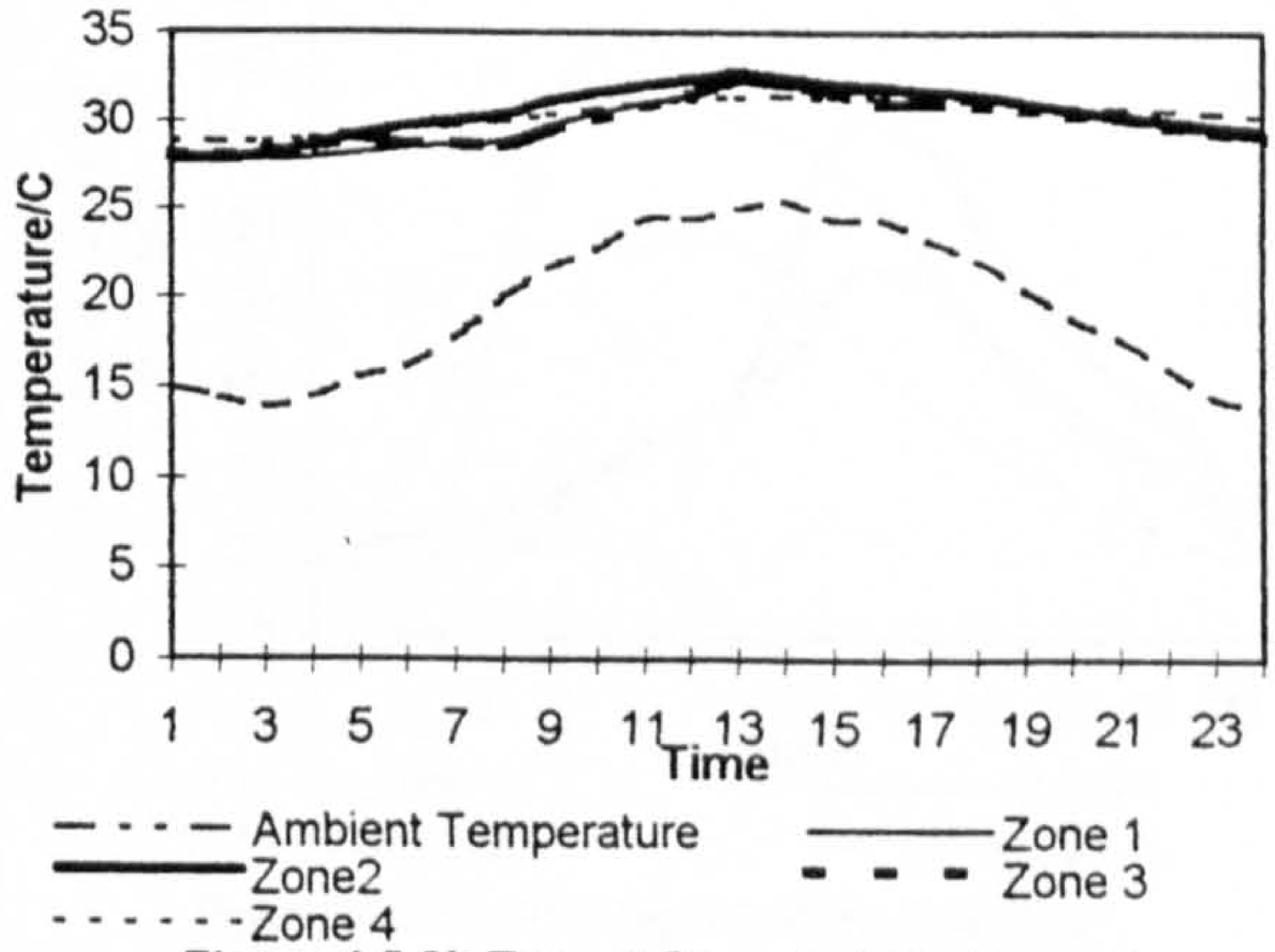


Figure 4.5.3j: Tenant Occupied Building, Zone Temperatures in October

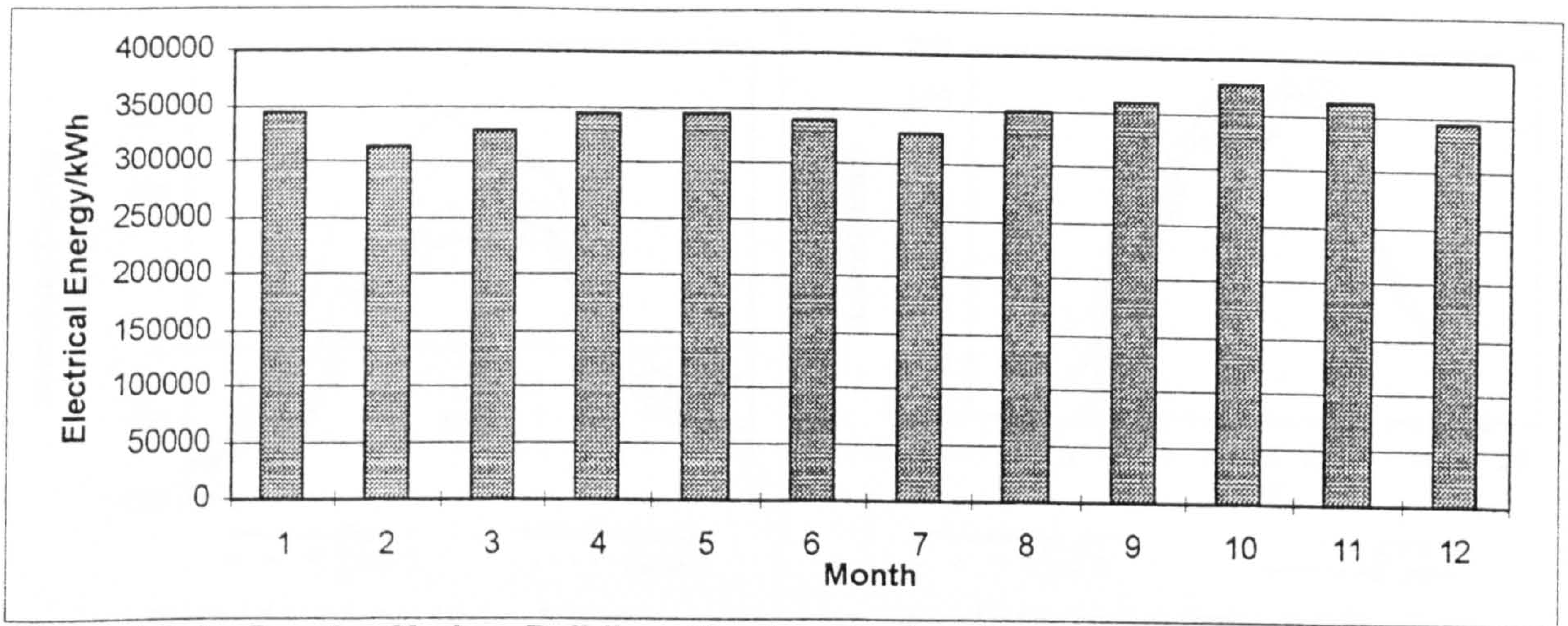


Figure 4.5.4a: Prestige Modern Building, Monthly Electrical Energy Consumption

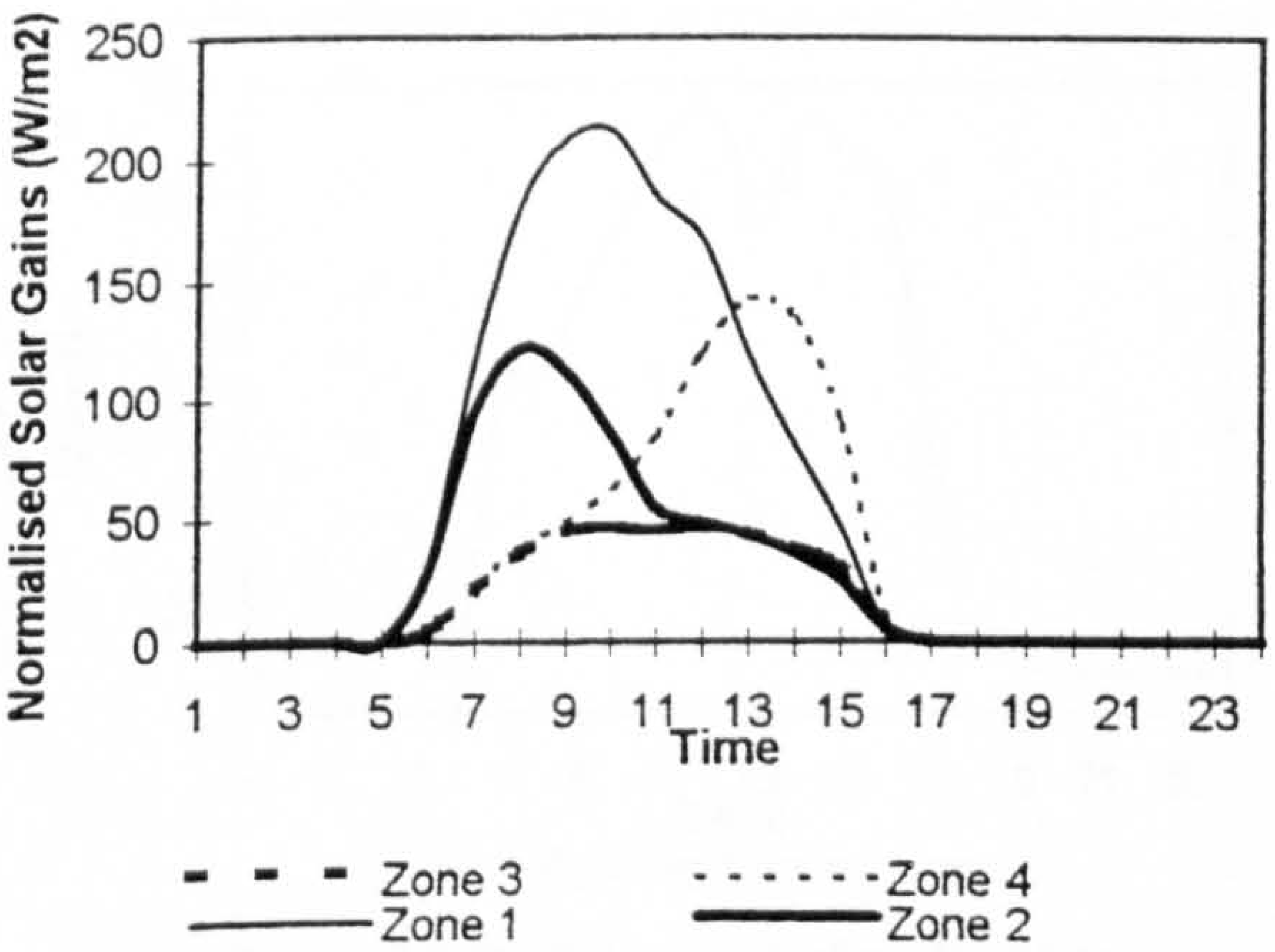


Figure 4.5.4b: Prestige Modern Building Zone Solar Gains in July

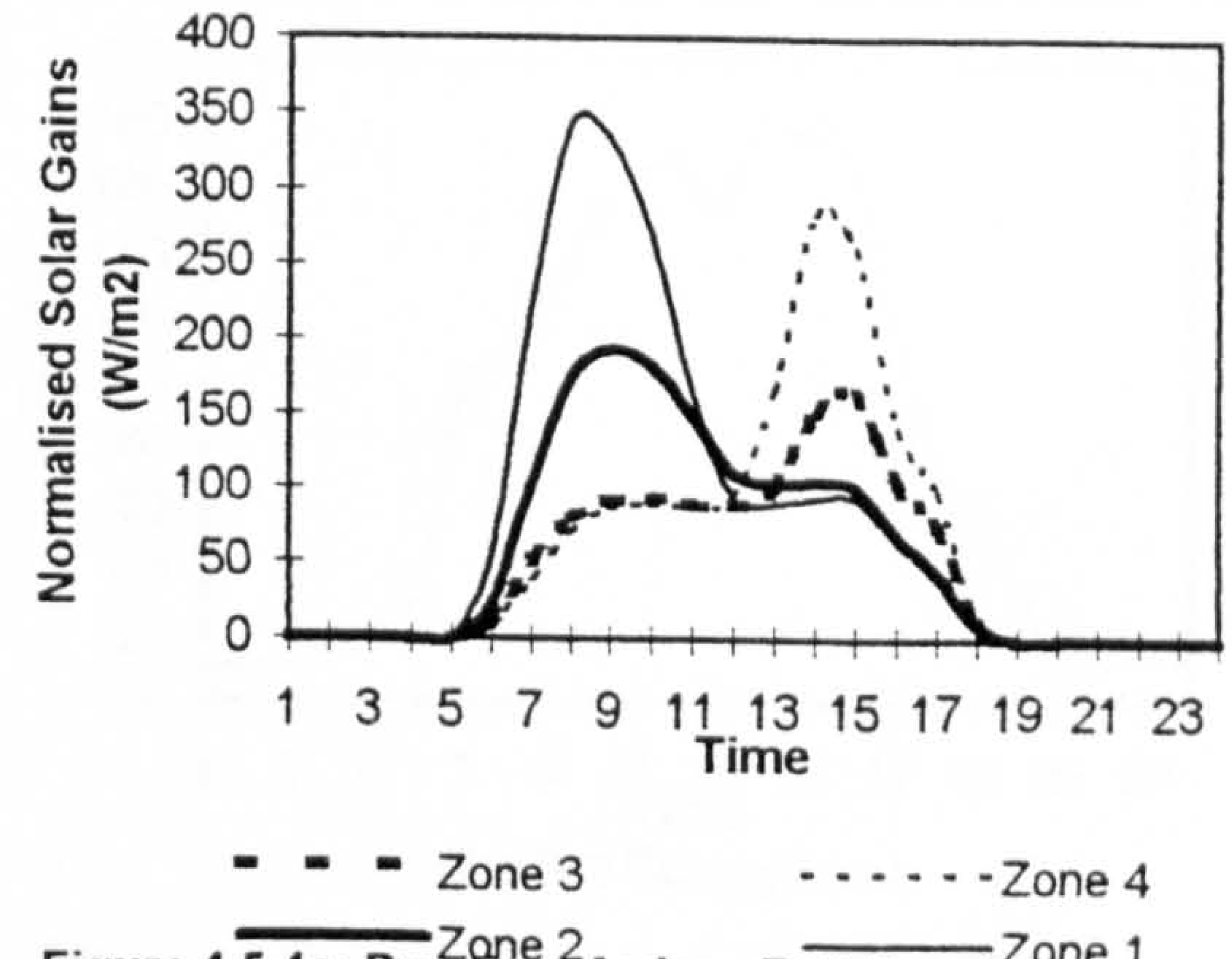


Figure 4.5.4c: Prestige Modern Building: Zone Solar Gains in October

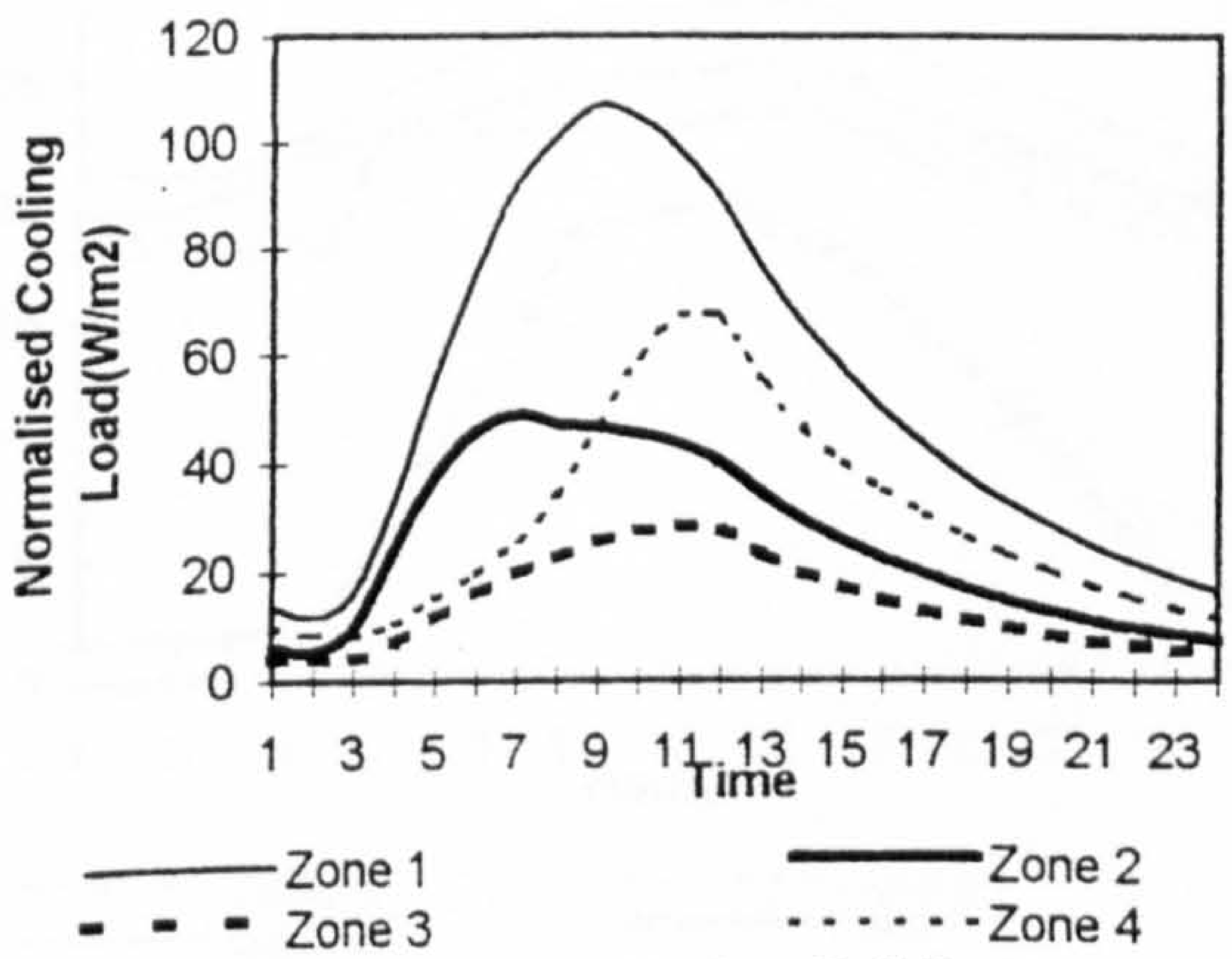


Figure 4.5.4d: Prestige Modern Building: Cooling Energy due to Solar Gains in July

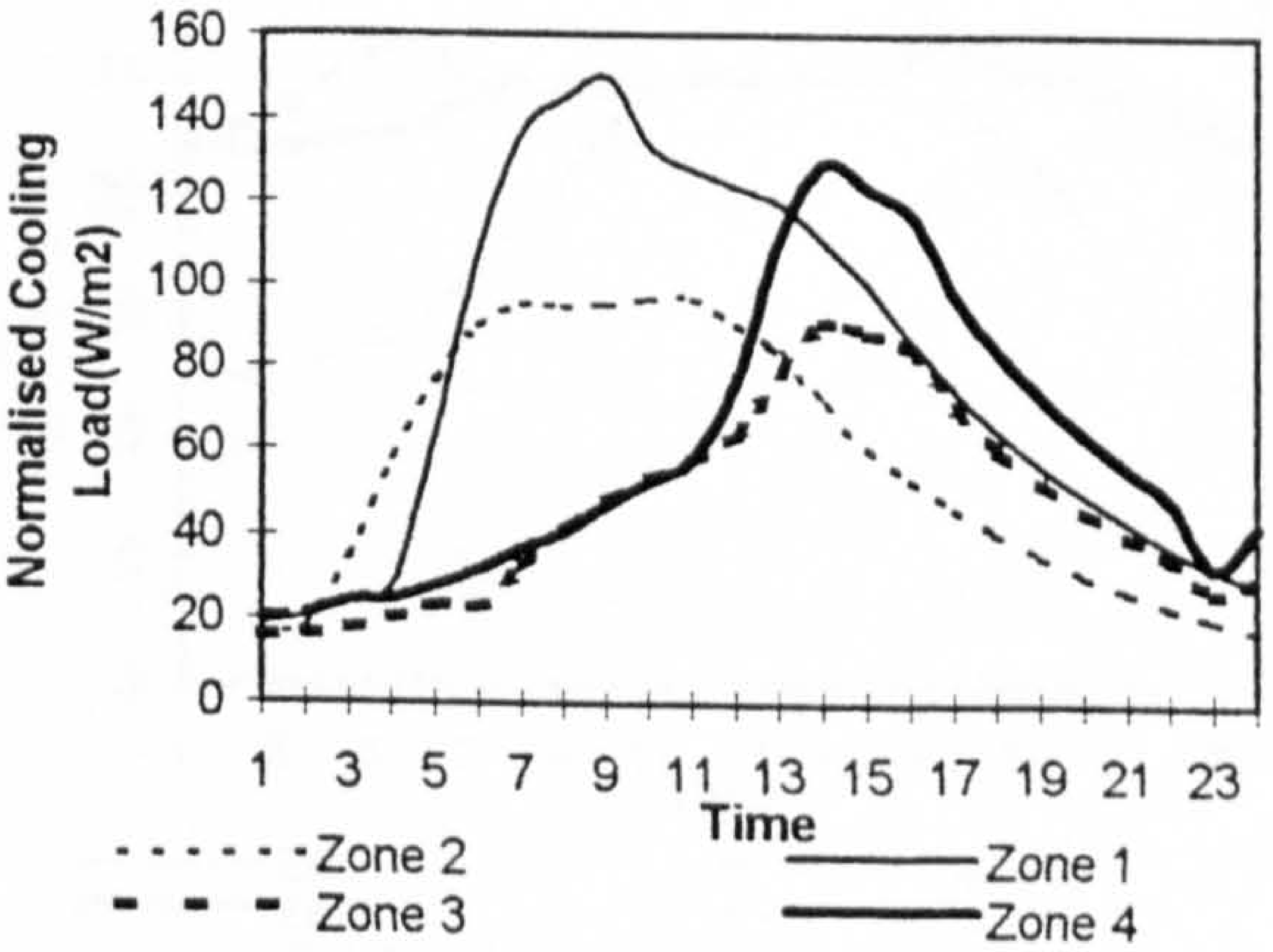


Figure 4.5.4e: Prestige Modern Building: Cooling Load due to Solar Gains in October

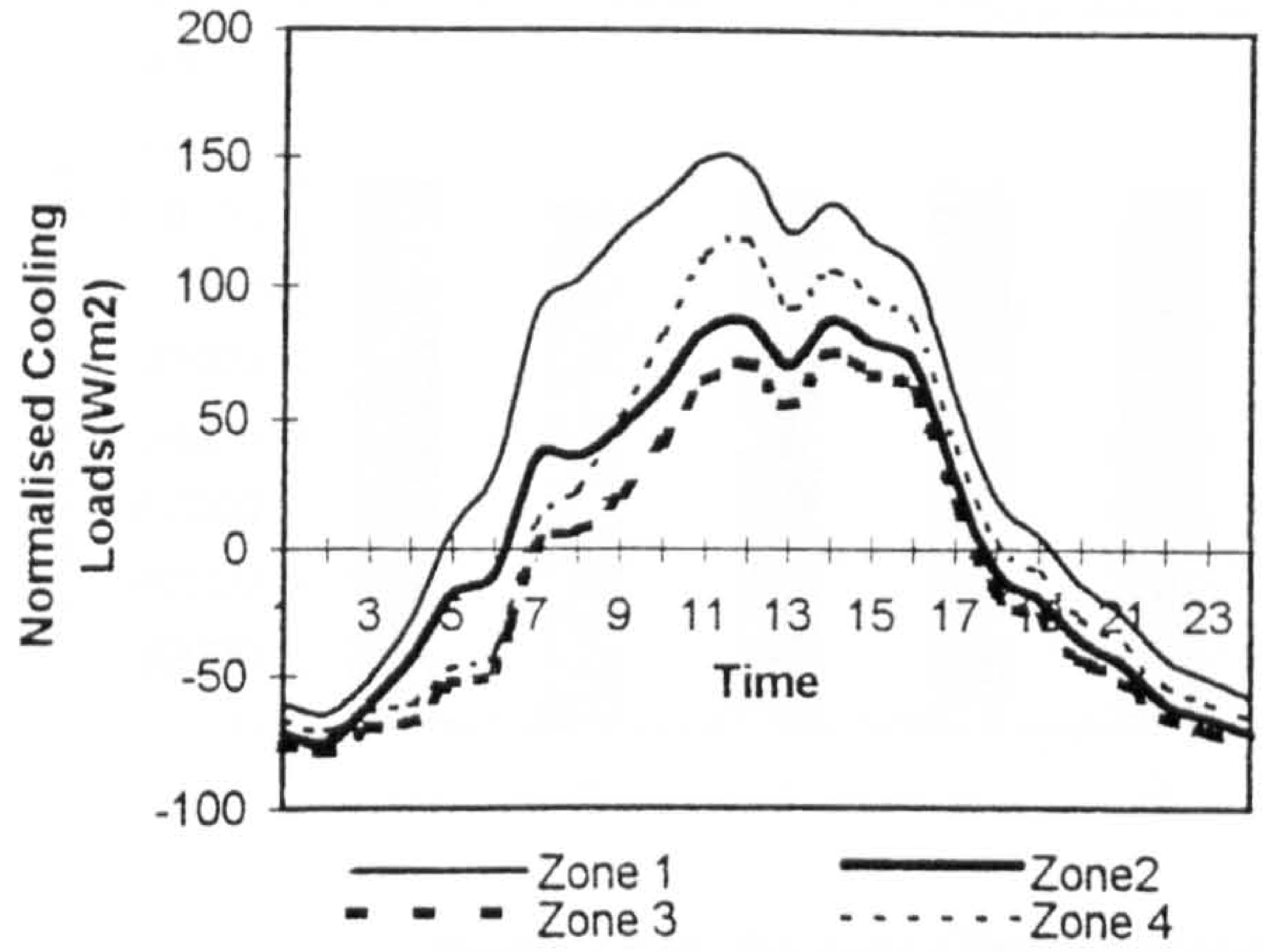


Figure 4.5.4f: Prestige Modern Building Cooling Loads in July

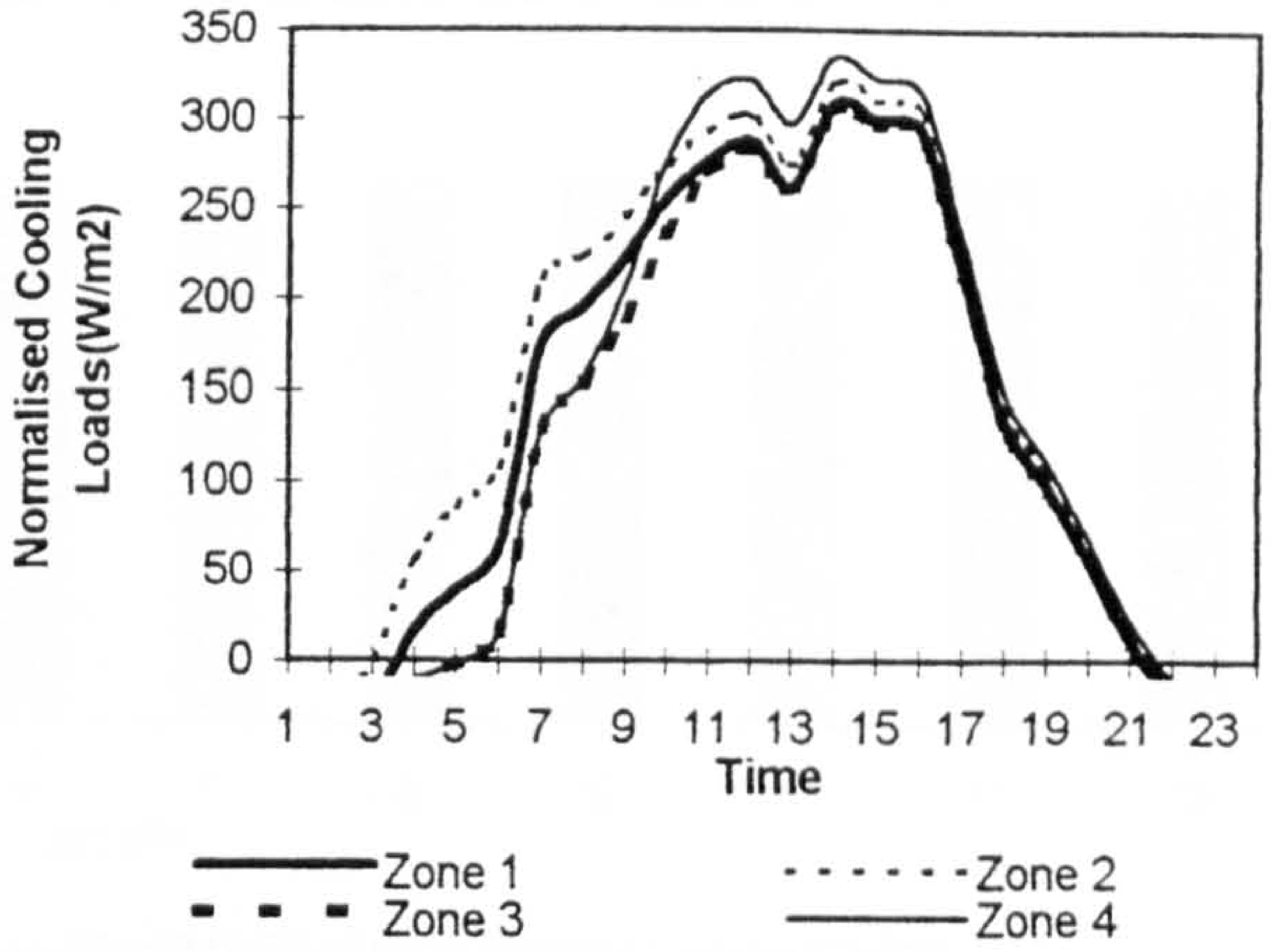


Figure 4.5.4g: Prestige Modern Building: Zone Cooling Loads in October

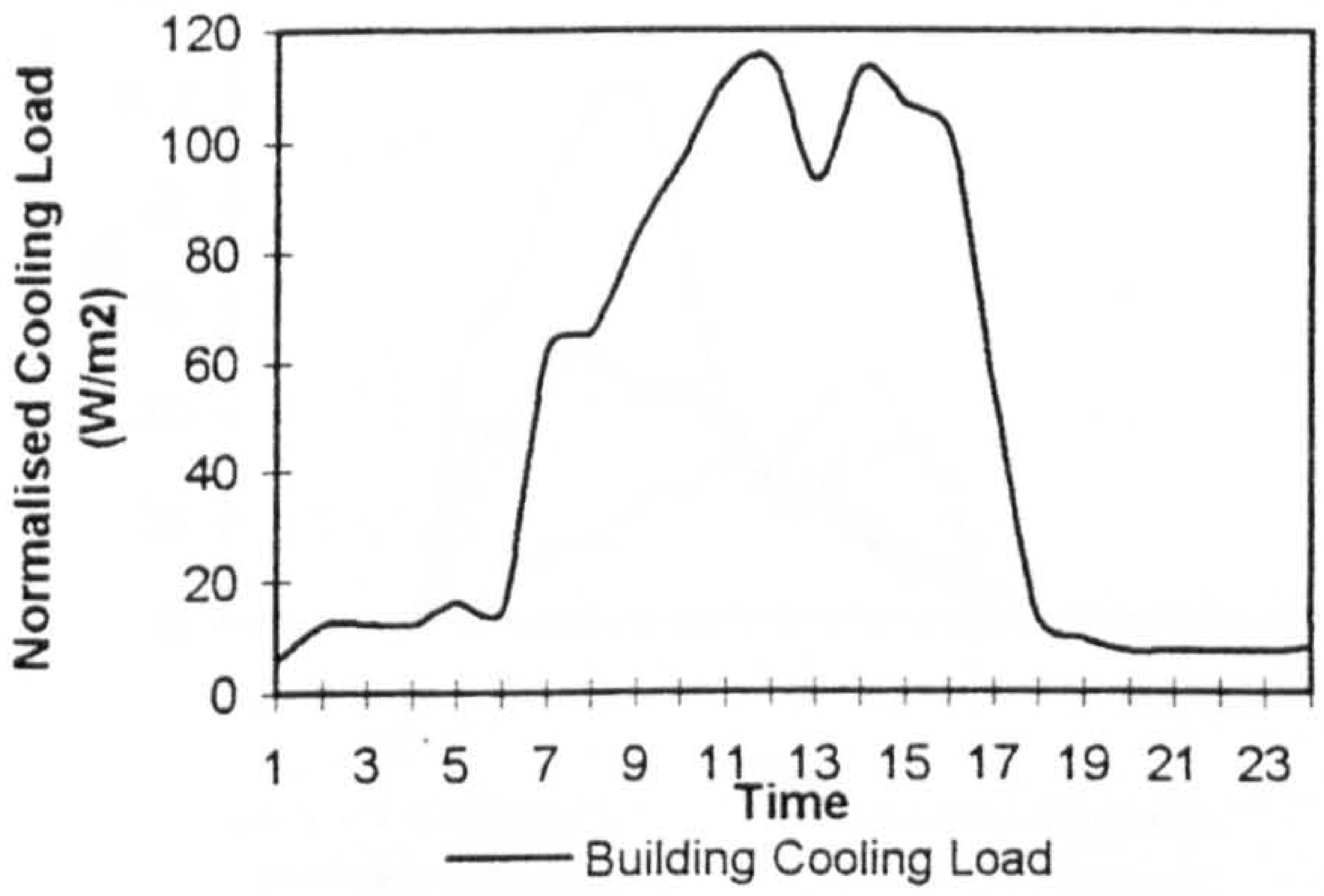


Figure 4.5.4h: Prestige Modern Building: Whole Building Cooling Load in July

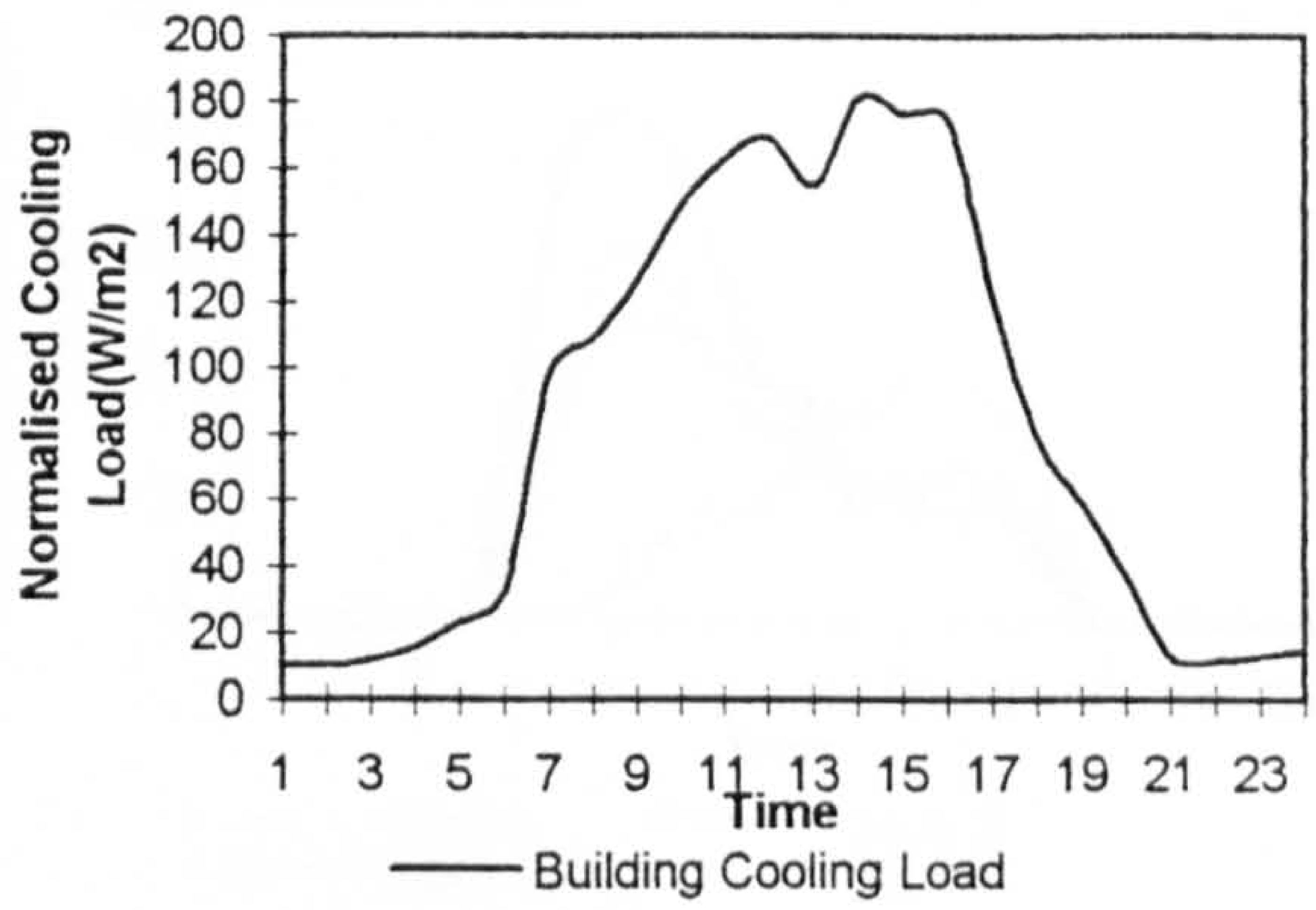


Figure 4.5.4i: Prestige Modern Building: Whole Building Cooling Load in October

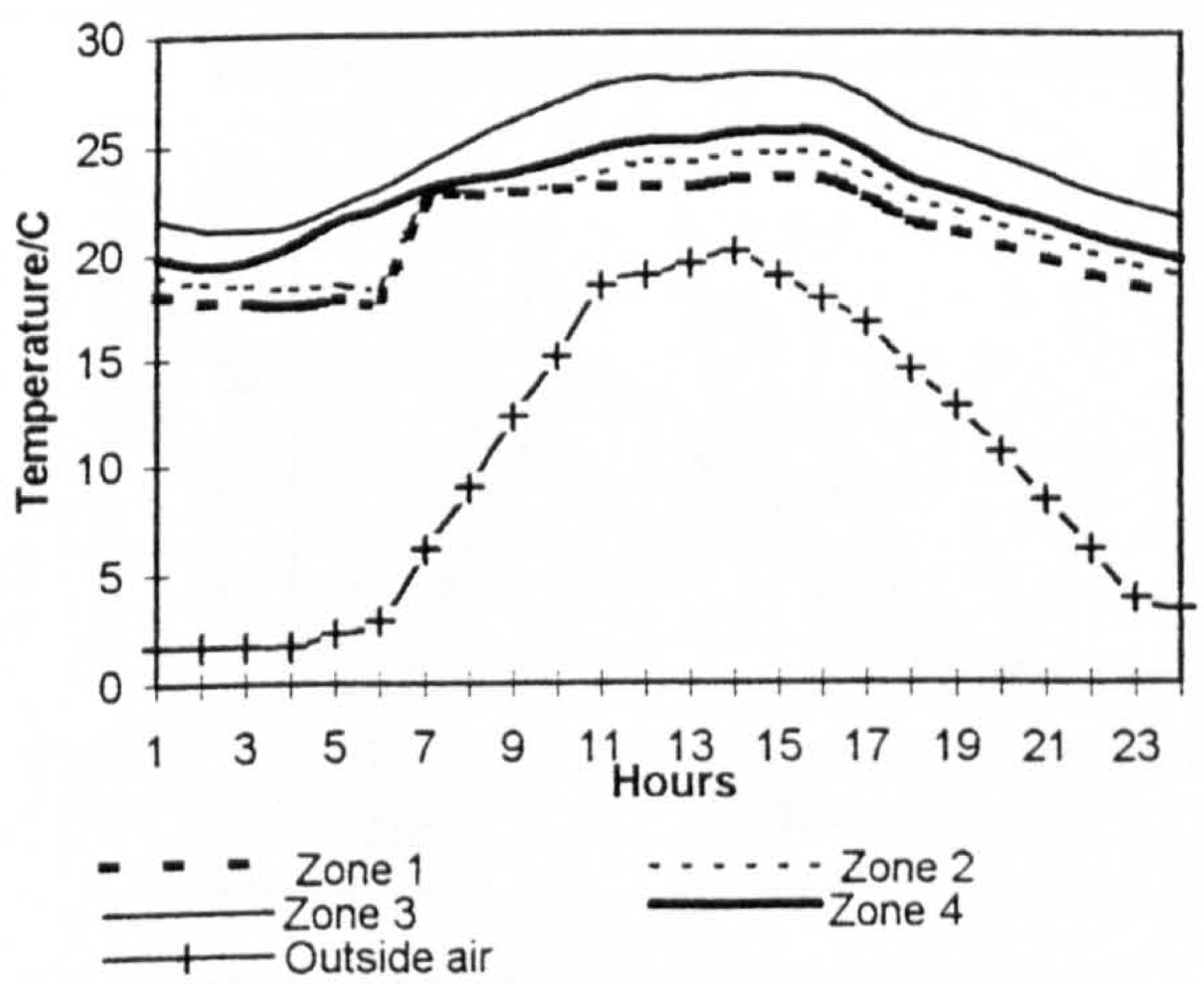


Figure 4.5.4j: Prestige Modern Building: July Zone Temperatures

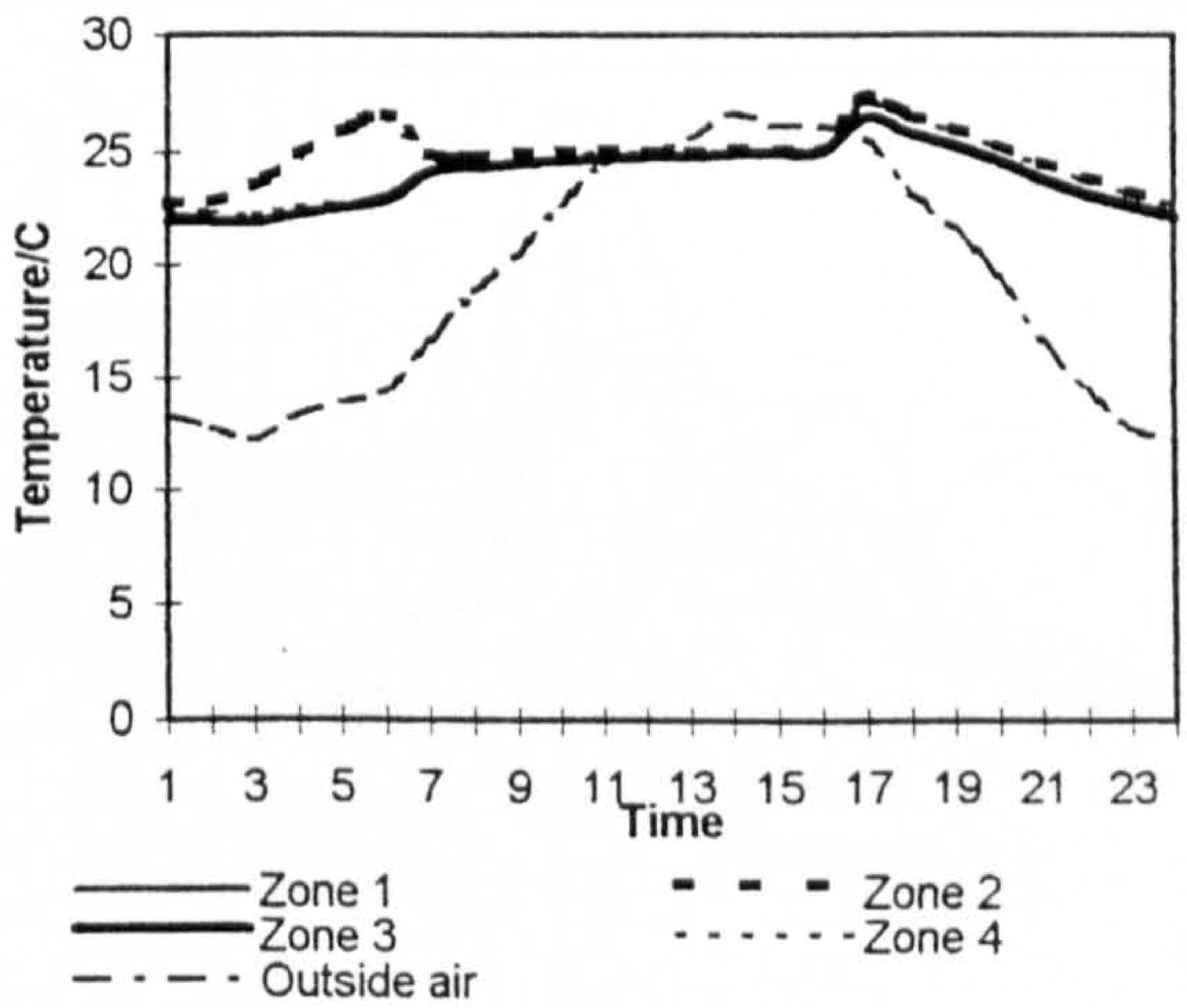


Figure 4.5.4k: Prestige Modern Building, Zone Temperatures in October

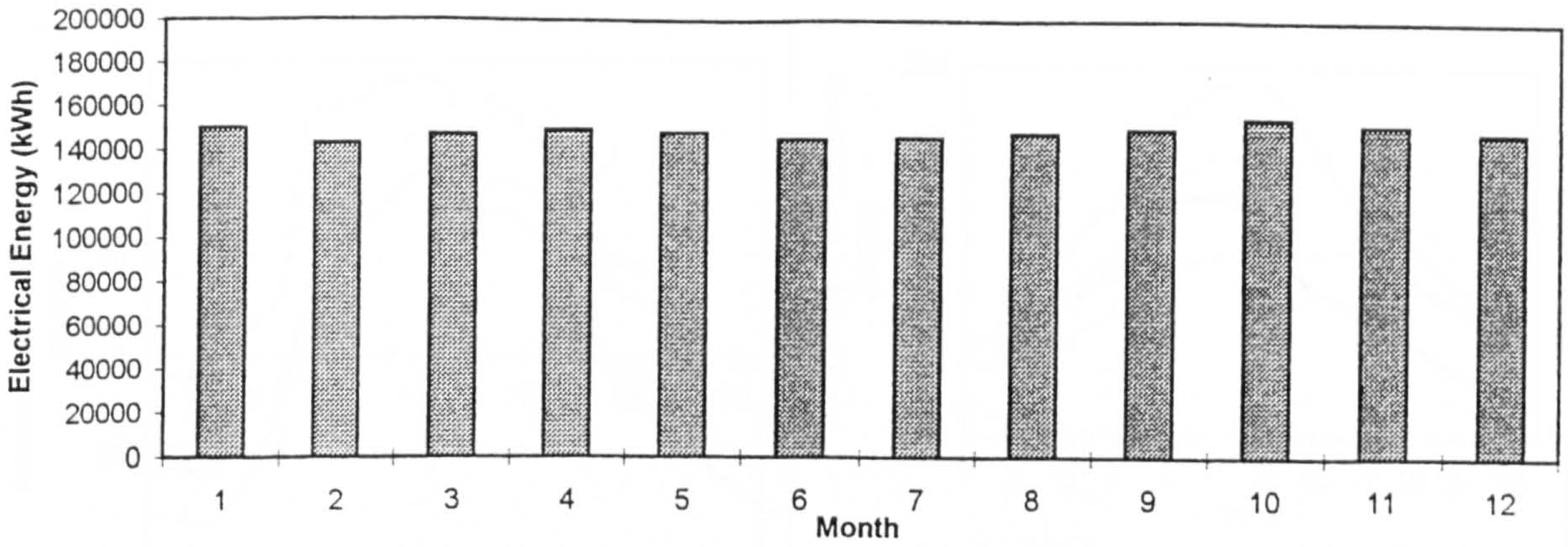


Figure 4.5.5a: Passively Ventilated Building, Monthly Electrical Energy Consumption

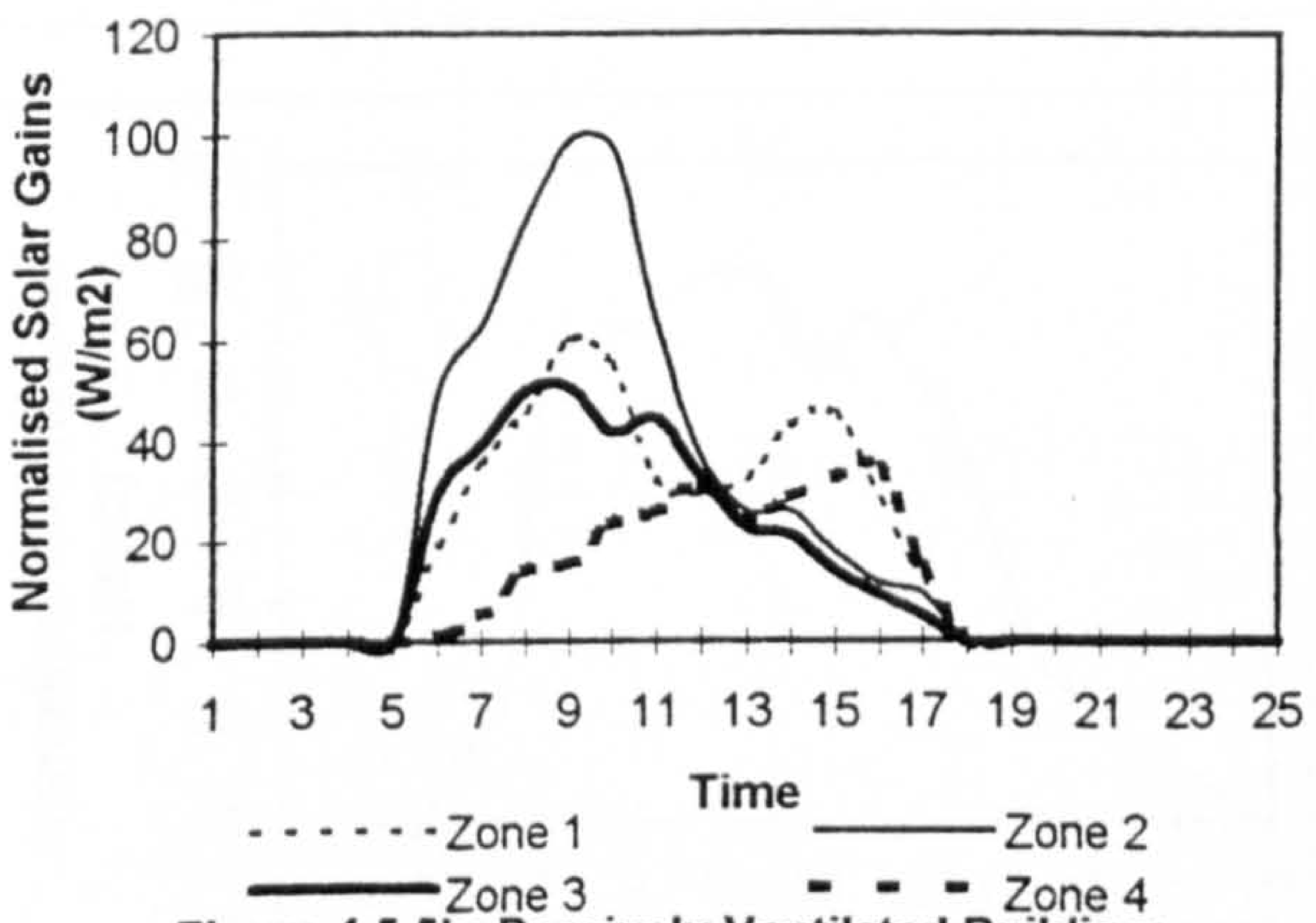


Figure 4.5.5b: Passively Ventilated Building: Solar Gains in July

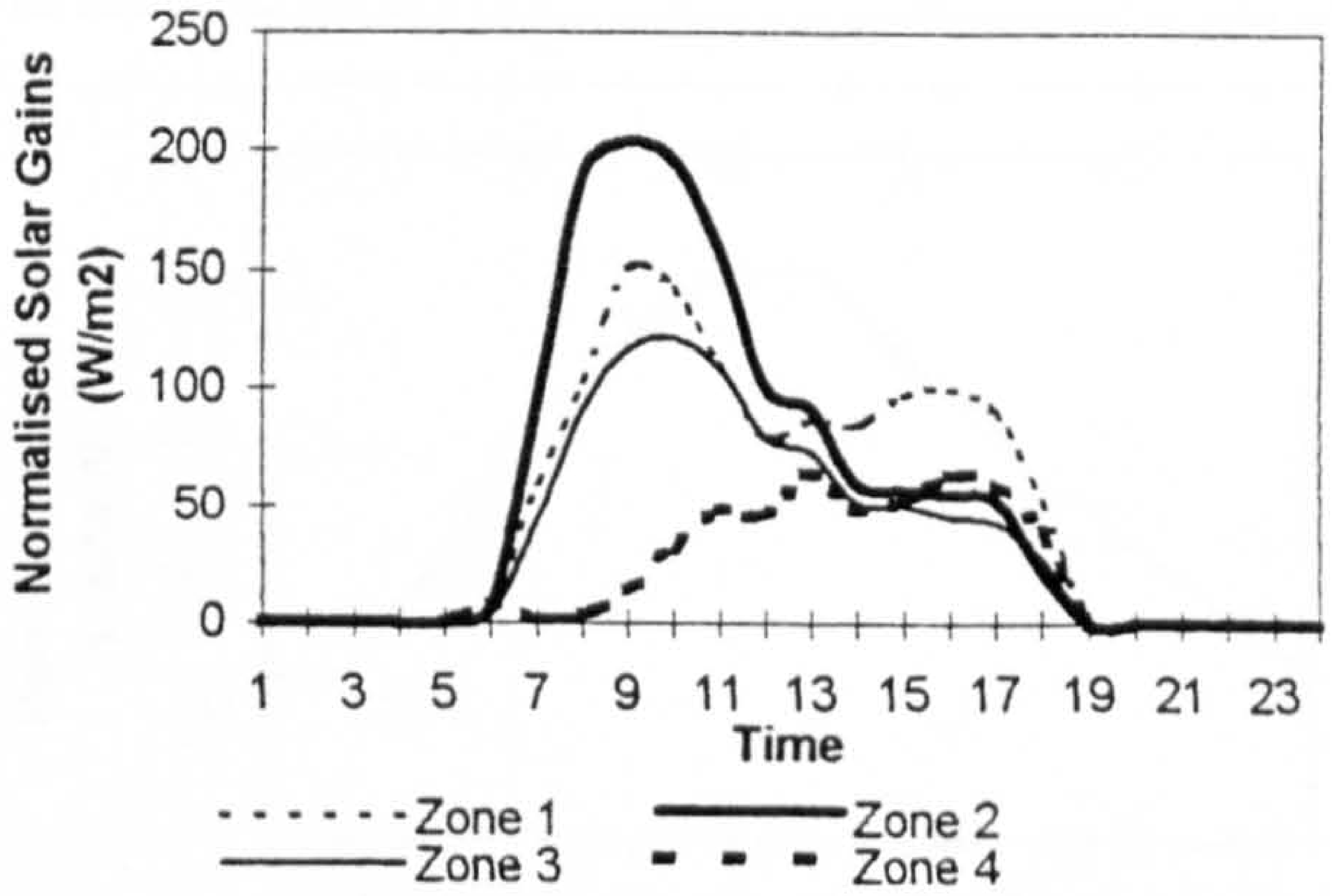


Figure 4.5.5.c: Passively Ventilated Building: Zone Solar Gains in October

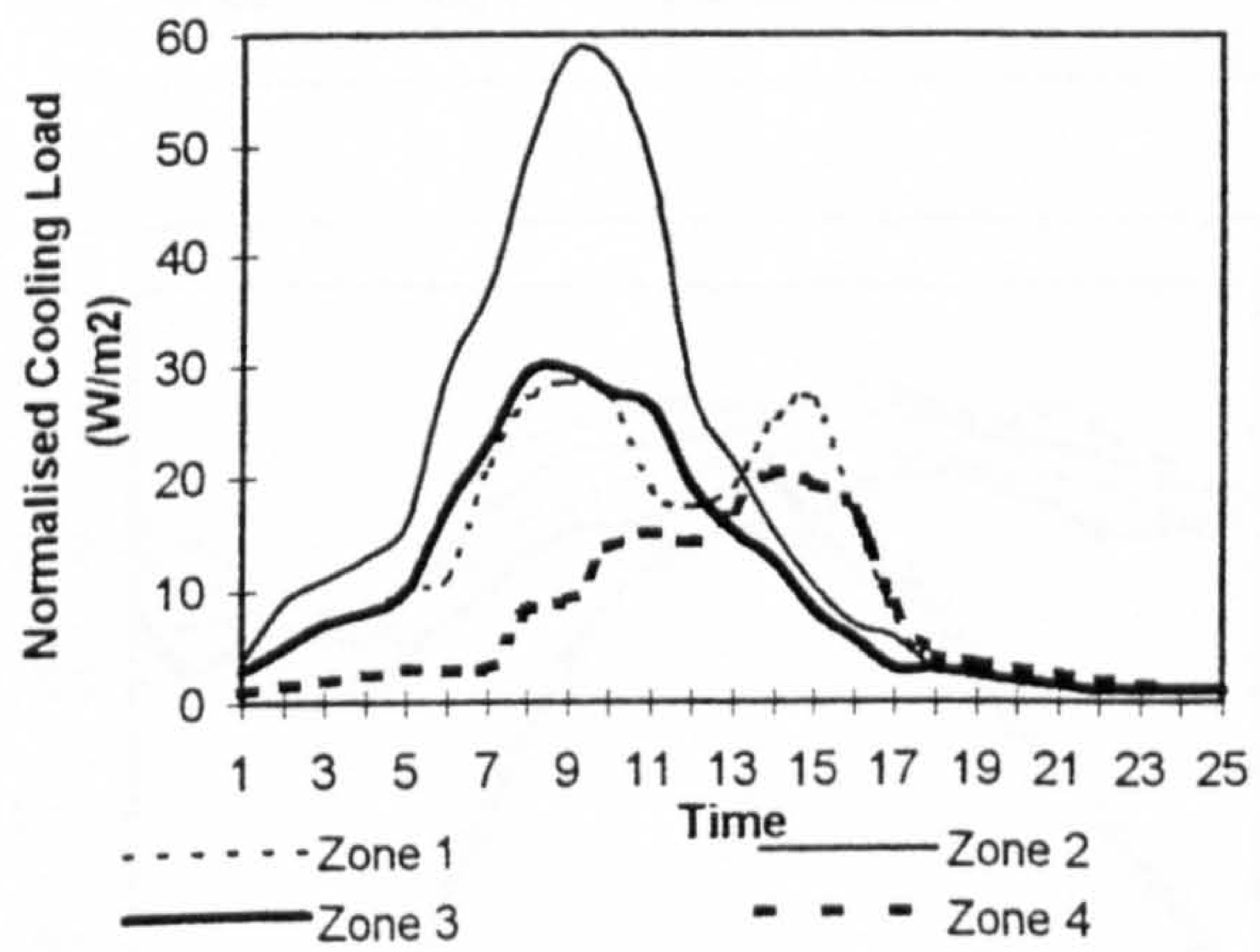


Figure 4.5.5d: Passively Ventilated Building: Cooling Load Due to Solar Gains in July

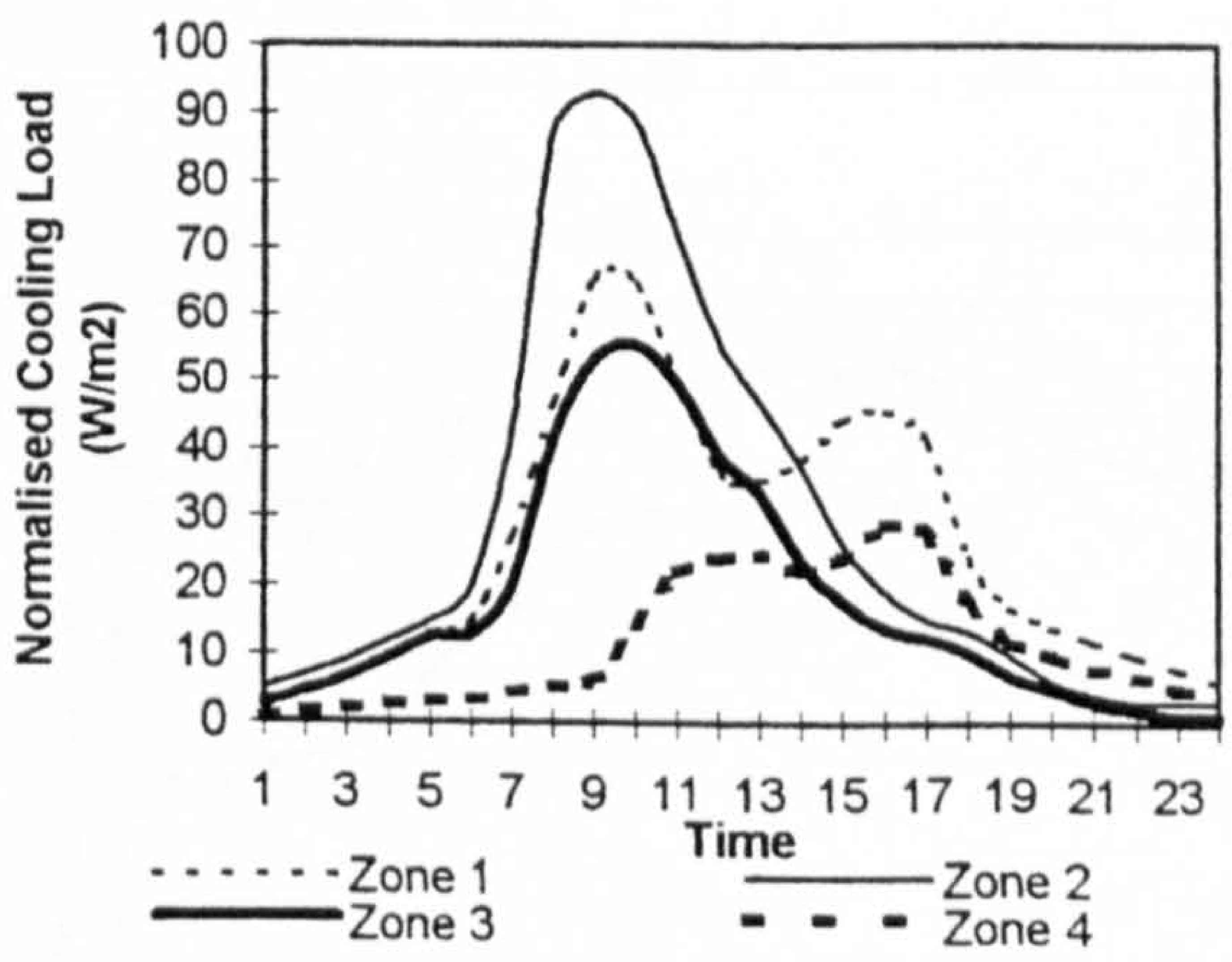


Figure 4.5.5e: Passively Ventilated Building: Cooling Load due to Solar Gains in October

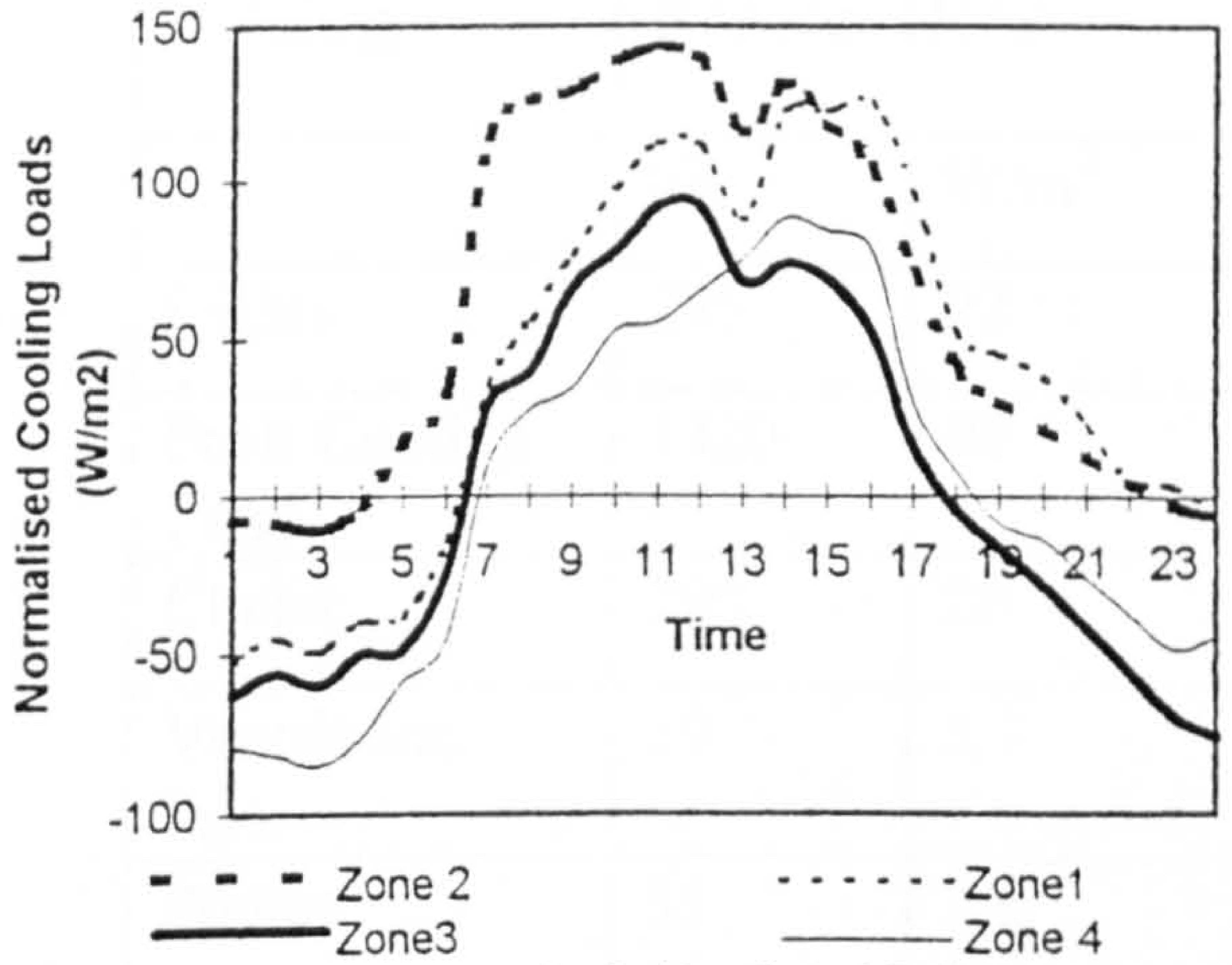


Figure 4.5.5f: Passively Ventilated Building: Zone Cooling Loads in July

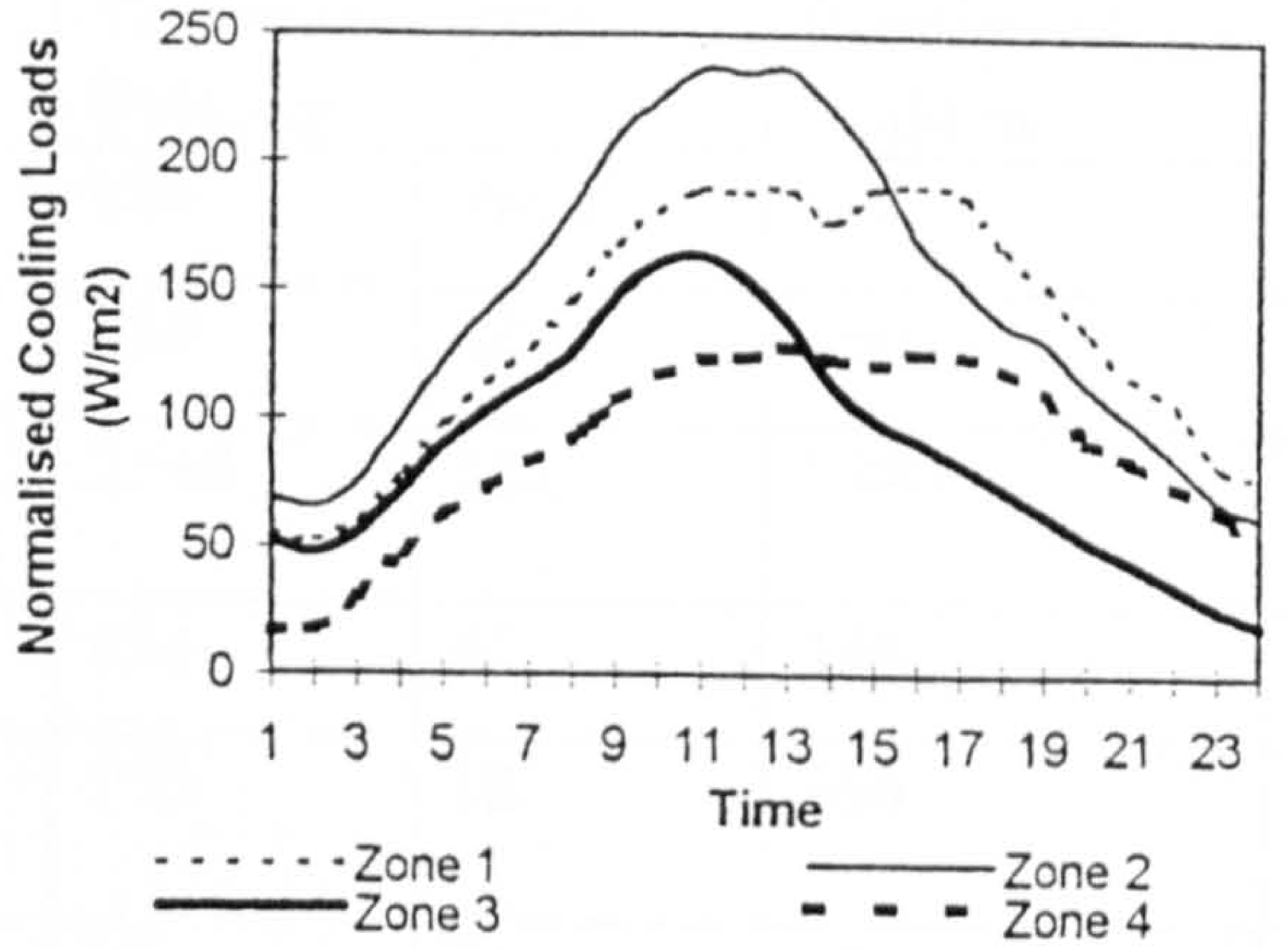


Figure 4.5.5g: Passively Ventilated Building: Zone Cooling Loads in October

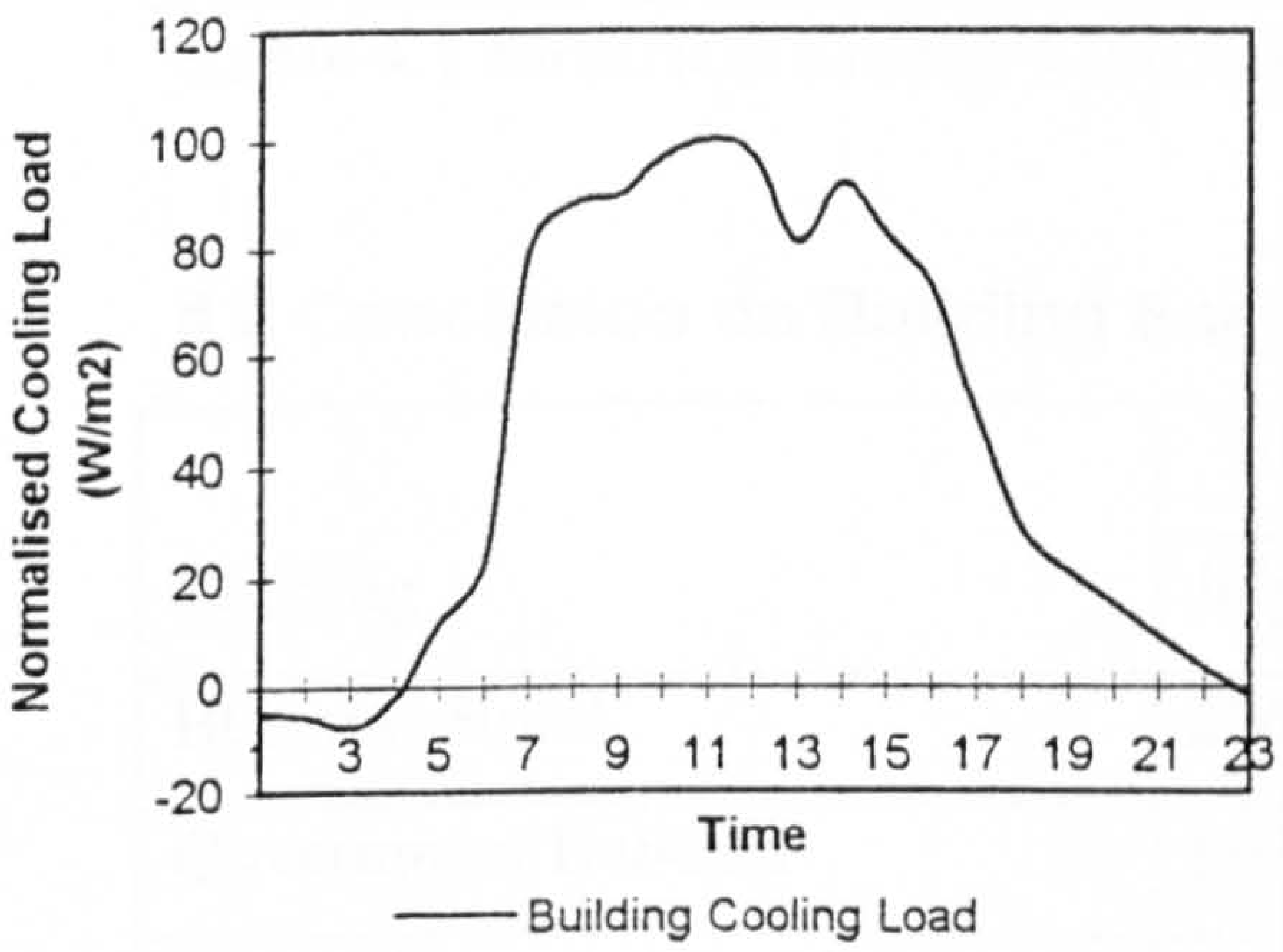


Figure 4.5.5h: Passively Ventilated Building: Whole Building Cooling Load in July

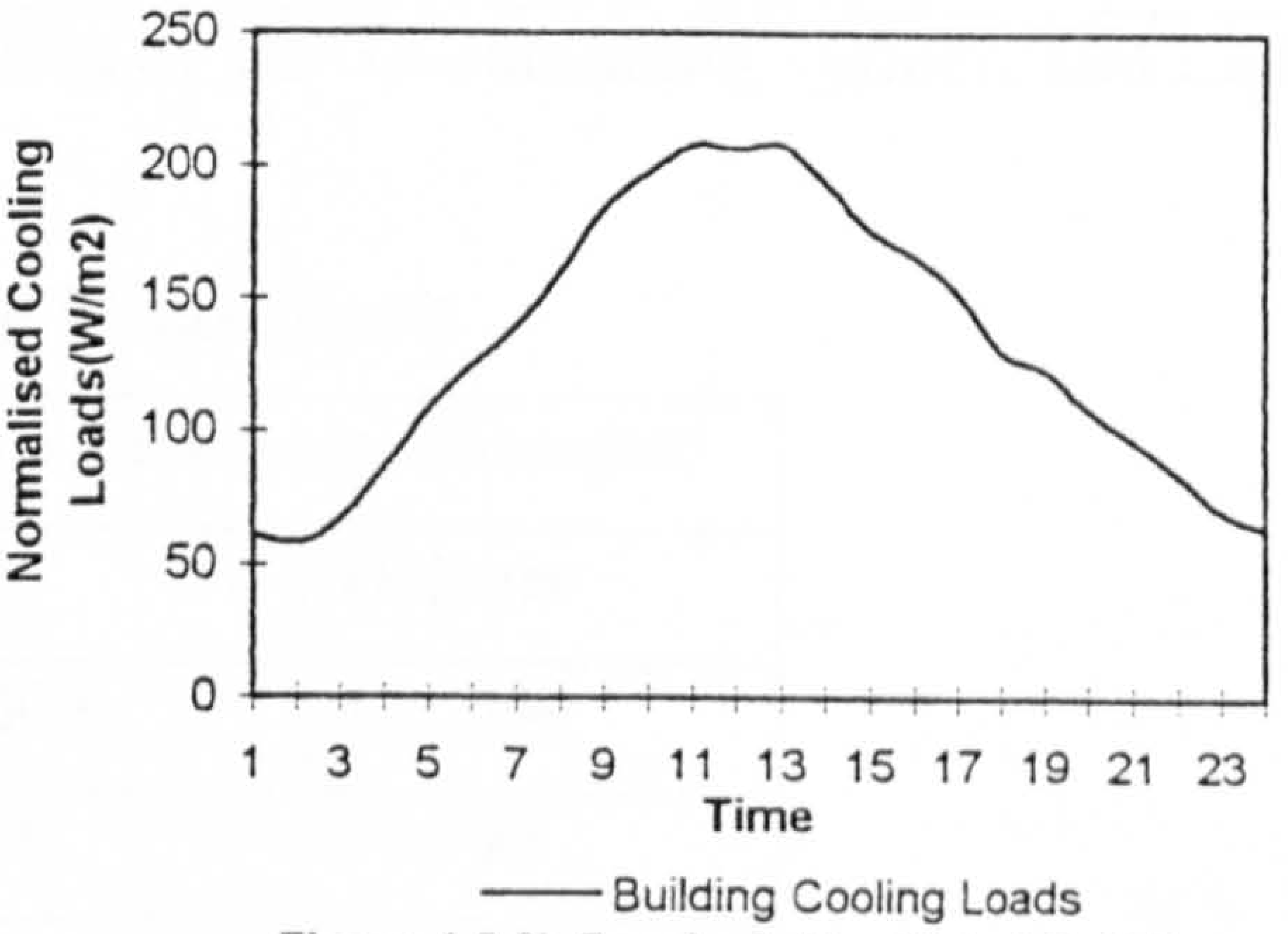


Figure 4.5.5i: Passively Ventilated Building: Whole BuildingCooling Load in October

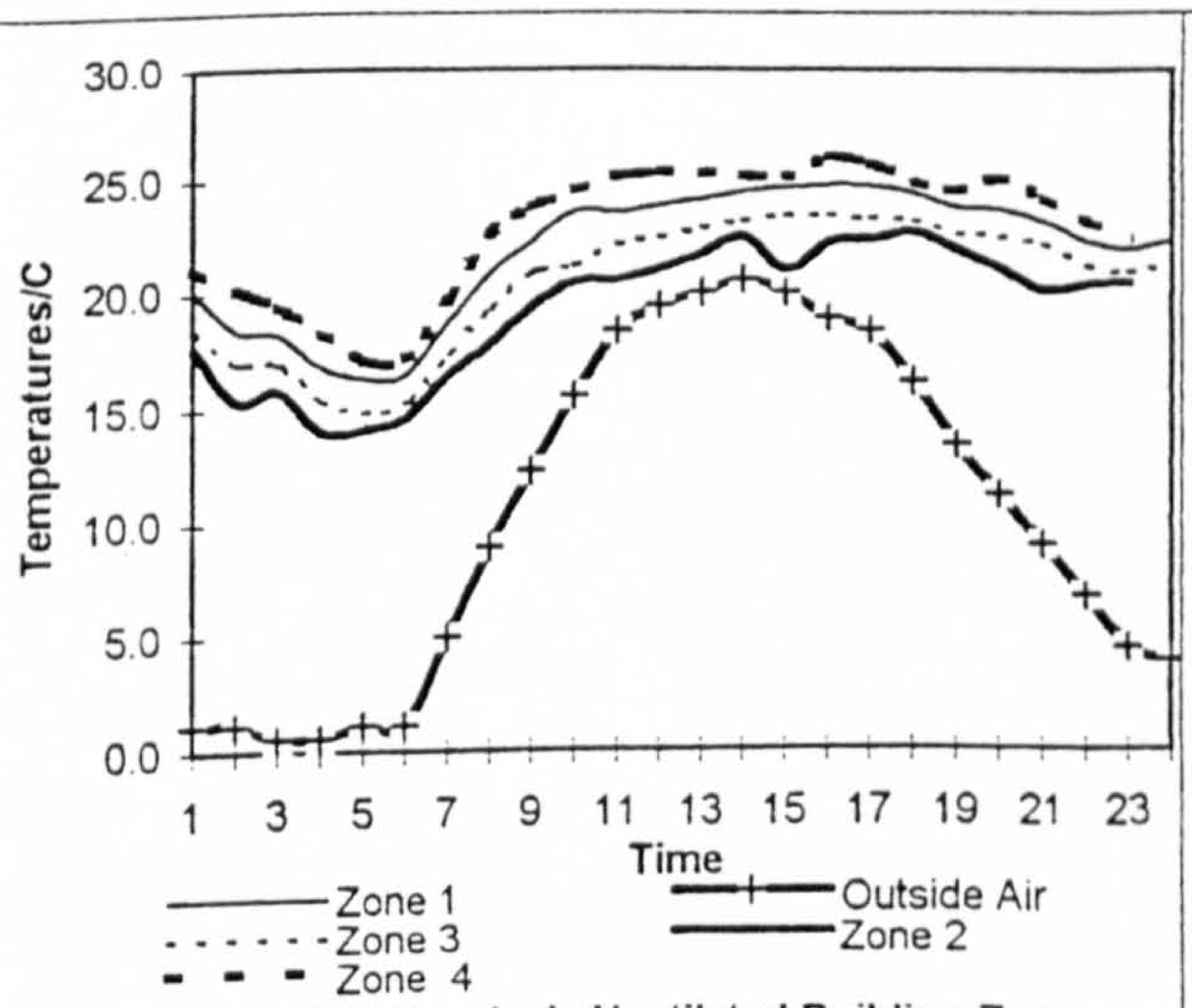


Figure 4.5.5j: Passively Ventilated Building Zone Temperatures in July

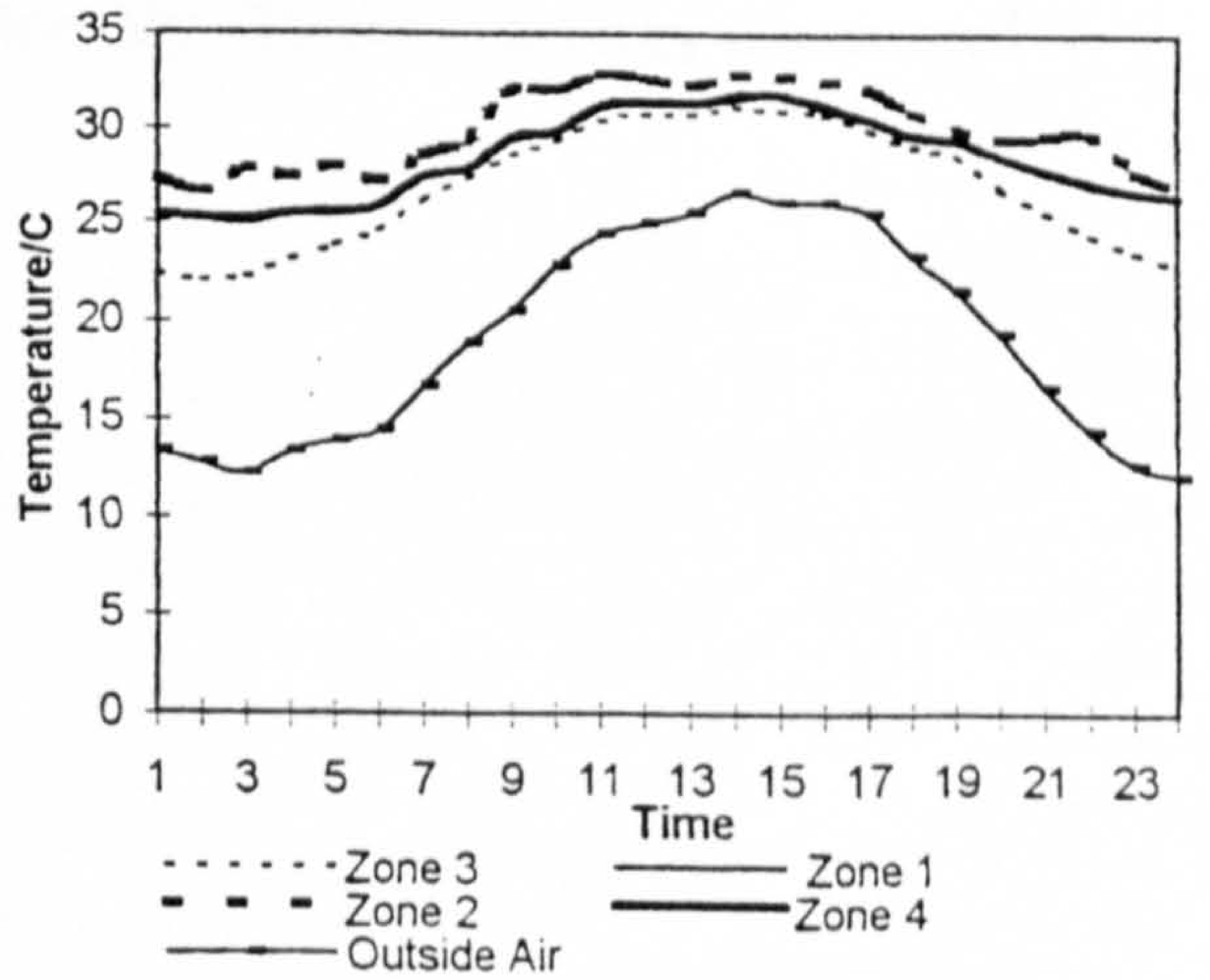


Figure 4.5.5k: Passively Ventilated Building: Zone Temperatures in October

Building	Business Hotel		Tenant Occupied Building		Prestige Modern Building	
	kW	W/m^2	kW	W/m^2	kW	W/m^2
Lights	295	22	310	32	260	34
Peak Cooling Load	1320	98	2144	225	1740	230
Chiller	280	20	434	45	386	49
Ventilation Fans	59	3.7	170	18	169	21
Pumps	31	1.6	43	5	35	5
Heat Rejection	61	3.0	85	9	78	8
Total HVAC	456	28	732	77	670	83

Table 4.1 Electrical Energy Consumption by Air-Conditioning Systems and Lights

4.6 Conclusion on Building Energy Simulations

Building	Electrical Energy Consumed	
	July	October
Business Hotel	296,000	321,000
Government Building	59,000	91,000
Tenant Occupied Building	254,000	276,000
Prestige Modern Building	330,000	360,000
Passively Ventilated Building	143,000	152,000

Table 4.2Minimuma and Maximum Monthly Electrical Energy Consumed

Building	Maximum Solar Gains		Maximum Zone Cooling Loads		Maximum Zone Temperatures	
	July	October	July	October	July	October
Business Hotel	177	210	58	155	23	27
Government Building	175	300	200	330	28	31
Tenant Occupied Building	95	175	153	300	28	30
Prestige Modern Building	200	340	150	340	26	27
Passively Ventilated Building	105	200	140	230	25	32

Table 4.3: Maximum Zone Solar Gains, Cooling Loads and Temperatures

Month	Building Cooling Loads				
	Business Hotel	Government Building	Tenant Occupied Building	Prestige Modern Building	Passively Ventilated Building
January	1318	3332	1916	1518	2167
February	1314	3225	1569	1494	2139
March	1302	3303	1673	1568	2174
April	1299	2458	1421	1257	1954
May	897	1916	873	987	1299
June	831	1632	847	901	1113
July	778	1543	800	899	1100
August	1036	2025	1124	1085	1848
September	1304	3113	1398	1242	2061
October	1320	3427	2144	1740	2213
November	1314	3385	1932	1636	2192
December	1312	3329	1904	1504	2179

Table 4.4: Maximum Building Cooling Loads for Each Month

The energy consumption in the exemplar buildings clearly shows the strong influence of solar energy on their electrical energy consumption. The data shown in Figures 4.5.1a, 4.5.2a, 4.5.3a, 4.5.4a and 4.5.5a are from building energy audit equipment and energy bills. The differences between the energy consumed in each month for the buildings with air-conditioning systems is much greater due to the varying amounts of electricity consumed by the air-conditioning systems in different seasons. Even those buildings without full air-conditioning shows variations with the seasons.

There is a strong link between the orientation of a building and the cooling loads it receives. The Prestige Modern Building receives the highest zonal solar gains because it has a high window to wall ratio on the north and north-eastern walls. This is shown by the fact that the peak of 320W/m^2 for Zone 1 occurs at 9am as shown in Figure 4.5.4c. It is followed by the Government Building with 300W/m^2 in its Zone 2. This is because it also has a high window to wall ratio of 70%. However, this zone has only one external wall facing the north. Therefore its peak occurs at noon. Zone 1 and Zone 3, which are to the west and the east of the Government Building have a very low window ratio. Their solar gains from the west and east are therefore very low. They therefore do not show afternoon and morning peaks, because the solar gains received from their north and south walls predominate. The low window to wall ratio therefore makes the solar gains on them appear much less than that on the north wall as shown in Figures 4.5.2a and 4.5.2b. This can be contrasted by the Prestige Modern Building which has the same wall to window ratio. The morning and afternoon peaks of 180W/m^2 and 250W/m^2 are for Zone 2 and Zone 4 which have walls directly facing the East and West respectively. Zone 3 also shows an afternoon peak of 150W/m^2 because it has a south west facing wall.

The Tenant Occupied Building and the Passively Ventilated Building have the lowest solar gain peaks of 175W/m^2 and 200W/m^2 respectively. The Tenant Building has a low window to wall ratio of 40% and these windows have a brown tint. The windows are also not adjacent to each other as on the Government Building or on the Prestige Modern Building. However, solar radiation through the window contributes only 40%, while gains from lights, people, equipment, and the air-conditioning plant contribute 50%. The Tenant Occupied building, because of its high equipment and people density has a high cooling load of 225W/m^2 which is comparable with that of the Prestige Building which is 260W/m^2. The power required for the air-conditioning system is 77W/m^2. The potential

PV power for the building is 21W/m^2. Therefore the PV power would contribute 27% of the power for air-conditioning.

The Business Hotel has a very low cooling demand of 98W/m^2 which occurs at 8pm. This is because the Business Hotel was assumed to be unoccupied during the day. All the heat generating equipment was thus assumed to be off, except when the occupants were in, which was in the evening. This building cooling load requires an air-conditioning plant consuming a total of 28W/m^2. This means that this would be 45% of the total building power demand. The potential contribution of PV on the Business Hotel is 21W/m^2. This is 75% of the power required for the air-conditioning system. The cooling load can be further reduced, by shading as shown in Chapter 5. This means that the PV power can supply the power required for the air-conditioning system. Here the maximum power of the air-conditioning system is considered. However, most of the times the ventilation fans operate between 50-80%. This further reduces the power required for the air-conditioning plant and increases the contribution of PV .

The Prestige Modern Building also has high peak zone and building cooling loads of 340W/m^2 and 230W/m^2 as shown in Figure 4.5.4g and Figure 4.5.4i. Comfort condition are maintained by a CAV two pipe fan coil air-conditioning system. This consumes 83W/m^2 of electricity. The potential output of PV modules on it is 20W/m^2. This means that it can contribute 26% of the power required by the air-conditioning plant. The Prestige Building was simulated in July with no air-conditioning plant. However, there is less variation of monthly electrical energy in Figure 4.5.4a, showing that the air-conditioning plant is switched on during the winter, either for heating or cooling.

The Passively Ventilated Building has the lowest cooling load of all the office buildings. Its peak cooling load is 230W/m^2. This is because of its small window to wall ratio and thermal massing of its walls. Figure 4.5.5k shows that the temperature in Zone 2 of the Passively ventilated Building exceeds 30°C at times. . However, this only occurs in one week of October, otherwise the rest of the year it is generally comfortable.

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Chapter 5

Methodologies of Integrating PV Systems in The Benchmark City

5.1 General Cladding Systems

The cladding that forms the distinct outer skin from the load bearing structure of a building may be of brick, stone, glass, metal or plastic which are designed such that they can be replaced in the event of damage or ageing. Cladding is therefore the most effective way PV modules can be integrated onto a building, as the outer wall surfaces receive direct sunlight for many hours during the day. In the case of buildings in the benchmark city the north, north-east and north-west facing walls are most suited for this purpose as the variation of the output during the day can be modified depending on whether modules face north-east for morning peaks or they face north-west for afternoon peaks. The electrical power generated by the PV cladding system would then contribute to the electrical demand of the building and, economics and policy allowing, it could be fed into the utility distribution system.

Commercial buildings undergo refurbishment every twenty to thirty years. This has proved to be particularly true for buildings constructed in the 1960s and 1970s in the UK[1]. In recent times their walls have had to be cladded to protect them from weather elements which were making the walls deteriorate. The buildings in Zimbabwe of a similar age where built using modifications of similar standards[2]. Although the weather is not as harsh to the building wall as it is in the UK, the walls on these buildings will in the long run also need to be refurbished. The avoided costs involved in the refurbishment, just like the avoided costs involved in a new installation means that the reduction in the effective capital cost of the PV system can be considered for both new and old buildings. Since PV systems generate electricity at a rate determined by the solar irradiation and the conversion efficiency of the modules, their output depends on the orientation of the modules. The traditional techniques of wall cladding have almost always been to have the cladding flush with the wall, meaning that if PV modules are to directly displace them they would be mounted vertically. This is far from the optimal orientation required for installations in Zimbabwe In higher latitudes a vertical orientation would enhance the output in winter and reduce it in summer. While this would be positively and negatively compensatory respectively for optimal sizing in these latitudes, it would always have a negative effect in latitudes similar to that of Zimbabwe.

The complexity of installing the modules at an optimal orientation is compounded by the constraints imposed by the fixings and connections. A larger size of components with dimensions identical to the existing cladding elements (say 2m x 1.2m(typical curtain walling panel size) as opposed to 1m x 0.5m (typical solar module size)) could be advantageous[3]. However, this depends on the type of cladding. The existing types of cladding include curtain walling, rainscreen cladding, panel cladding and external shading. PV modules installed under these cladding systems are likely to have different performances. It is also likely that in building integrated applications, PV modules will be working under non-ideal conditions. The assessment of the output of the modules will therefore have to take into account not only tilt, orientation, temperature effects in as far as they affect the output of the modules but the protection of the modules as well.

Not only can excessive temperatures reduce module efficiency it can also damage the common module encapsulant which cannot withstand temperatures above 85°C for extended periods. The cladding system to be used at any one instant has to allow free movement of air at the back of the panels so that the heat that can accumulate there and cause temperature rises of up to 100°C is removed[4] . The integration must also avoid modules shading each other as this not only reduces the output, but it may cause damage to the modules by the hot spot effect if the cells within the modules are differentially shaded[5]. The building to building shading also determines which surface of a building can be used for installing photovoltaic systems.

Previous work has shown that the photovoltaic modules can be integrated into some cladding systems without modification to the design of the modules[6]. This applies to modules integrated as overcladding panels and as external sunshading devices. These systems do not require thicker glass than that already existing on the modules. They allow free movement of air behind the modules thereby allowing the use of the existing encapsulant. In the long run a common form of curtain walling such as the mullion/transom system may have to be considered for the integration of photovoltaic modules. The anticipated PV cladding system would consists of either double glazed or insulated sandwich panel.

5.1.1. Mulllion/Transom System

The mullion/transom system, shown in Figure C.1 of Appendix C is widely used in the construction of buildings where middle to high quality cladding system is required[7]. It consists of vertical members(mullions), horizontal members(transoms), transparent double glazed units or openable windows in the vision areas and opaque double glazed units or insulated pressed metal for the non-vision spandrel areas. The mullions can have a height of one or two floors of a building.

PV modules can be integrated into the double glazed units. The common make of the double glazed units is 6mm thickness for the panes and 12mm for the cavity. This contrasts with the composition of PV modules which have a sandwich of 3mm thick toughened glass, silicon wafers, encapsulant and backing sheet. The problem of replacing the 3mm glass with the 6mm glass can be solved and the modules can be considered for the non-visual spandrel. The modifications that are likely to be more demanding are the removal of heat generated during the operation of the modules[8] and the accommodation of wiring in the double glazed units without compromising the waterproofing .

The PV modules could be also be integrated as single glazed units fixed into transoms and mullions. The thickness of the PV module glass still needs to be a minimum of 6mm thick. The main disadvantage here will be that single glazing units are now limited in their application due to their low thermal performance and the limited attenuation of noise, while condensation on the inner surface could degrade the building contents and fabric. The first two disadvantages could be rectified by using a separate insulated panel installed into the cladding framework. The insulation could however raise the working temperatures within the modules to above 100°C thereby reducing the module efficiency and degrading the encapsulant. Alternatively, the PV modules could be incorporated into sandwich panels to displace the outer of the two metal sheets enclosing the insulating material. The problem of cooling of the modules still persists here. The modules could be spaced off from the sandwich panel curtain wall which will remain unaltered. This allows the free air circulation behind the modules which will keep their working temperatures relatively low. However, this again results in additional cost.

This system has many disadvantages when considered for building-integrated systems, especially in Zimbabwe. However, this system is the one being widely adopted by those building owners who are in a position to afford building-integrated systems[9].

5.1.2 Panel Systems

The panel system consists of large panels up to a storey high containing all necessary elements that the external building fabric could require. The non-vision areas is usually made of natural stone or metal with double glazed units in the vision areas. They are more suited to highly articulated facades finished in heavy materials like natural stone[10]. PV modules can be incorporated into them by displacing the facing material. This system is shown in Figure C.2 of Appendix C

5.1.3 Rainscreen Overcladding

Rainscreen overcladding systems are an external lightweight protective envelope on buildings. The PV modules could be integrated into the overcladding panels or they could be attached to the panels[11]. The disadvantages are that the modules in this case will also be most likely to be vertical making the system non-optimal in the Zimbabwean context . The system also faces problems of dimensional compatibility between the modules and the system which calls for a range of sizes of the modules. This system is shown in Figure C.3 of Appendix C

5.1.4 Shading Features

Shading features on buildings offer another opportunity for the incorporation of modules. The external shades are usually fixed or adjustable, metal or glass and large or small. The external louvres both horizontal or vertical are made of metal, timber or plastic[12] which can easily be replaced by the PV modules. The louvres could then be turned and adjusted automatically to provide maximum shade, matching the angle of the sun. The power for this operation which would be necessary when the sun is shining could be derived from the PV modules themselves.

5.1.5 The Exemplar Buildings

The systems considered above are all found in the benchmark city. The masonry cladding of the business hotel in Photograph A.1 of in Chapter 3 is a good example of a rainscreen overcladding. The curtain wall around the Prestige Commercial Office Building in Photograph A.4 in Chapter 3 is a good example of the mullion/transom system. Shading features are by far the most prevalent external features on buildings in the benchmark city. These range from the egg-crate overhangs on the government office building in Photograph A.2, to the extended concrete overhangs of the passively ventilated building in Photograph A.5 and the moveable shading systems in the buildings Photograph A.6.

5.2 Case Studies of Realised Demonstration Buildings: Comparison with Exemplar Buildings

The suitability of the exemplar buildings for the building-integrated is best illustrated by comparing with realised examples.

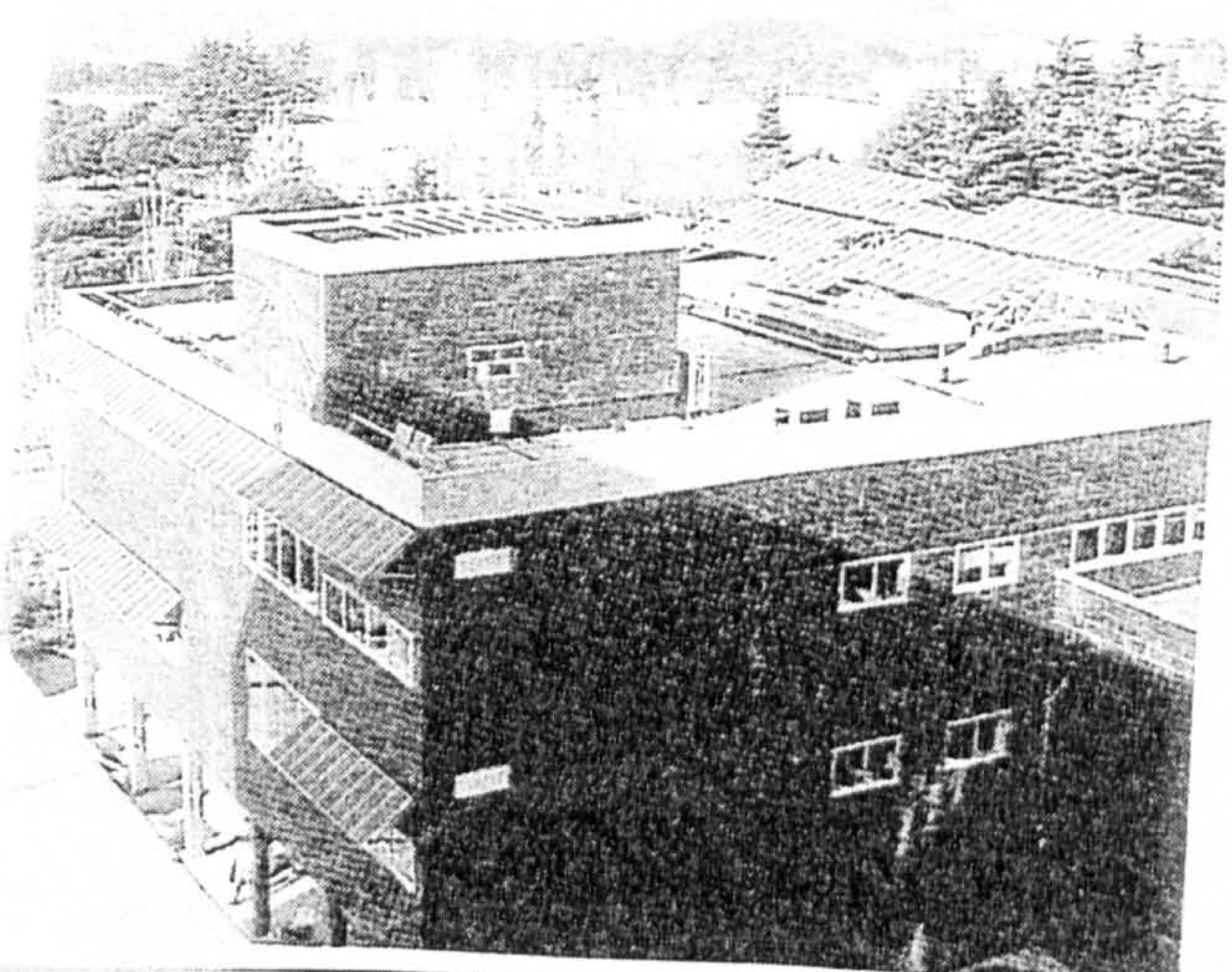
The business hotel and the government office building all have facades similar to those of the Northumberland Building in Newcastle upon Tyne, UK and the Swiss Federal Laboratory for Materials Testing and Research, in Switzerland. Each of the latter pair of buildings have photovoltaic systems on their facades with an installed capacity of 40kWp. Both are characterised by long east-west walls, which have a high proportion of glazing on both the north face and the south face. The Northumberland Building had a photovoltaic cladding system integrated into its wall after the original mosaic cladding and concrete fixings were found to be in such a poor condition that they had to be completely removed[13]. There was also a thermal environmental consideration to the renovation in that the windows had to be replaced with those with a higher thermal efficiency. These two factors created the opportunity for PV to be integrated onto the south facade of the building. The system consists of PV panels inclined at 13.5° to the vertical, thereby allowing the facade to take advantage of the winter sun, and to provide some shading to the windows during the summer when the building generally suffers from overheating[14]. The problems of constructional compatibility of PV were overcame by dividing the cladding into a series of units, approximately 3m by 1.3m in size each consisting of 5 PV laminates inserted into an aluminium powder coated frame and held in the frame by a structural silicon sealant. On the other hand the Swiss Federal Laboratory for Materials Testing and Research was constructed with energy conservation involving photovoltaics integrated into its plans from the beginning[15]. The compatibility of the photovoltaic system was enhanced by laminating the solar cells in extra-white translucent glazing. The solar panels on the south east were also used as an aesthetic element to enhance the horizontal structure of the horizontal wing. Those on the south west were designed to track the sun between the angles of 60° and 90° so that their output could be improved considerably.

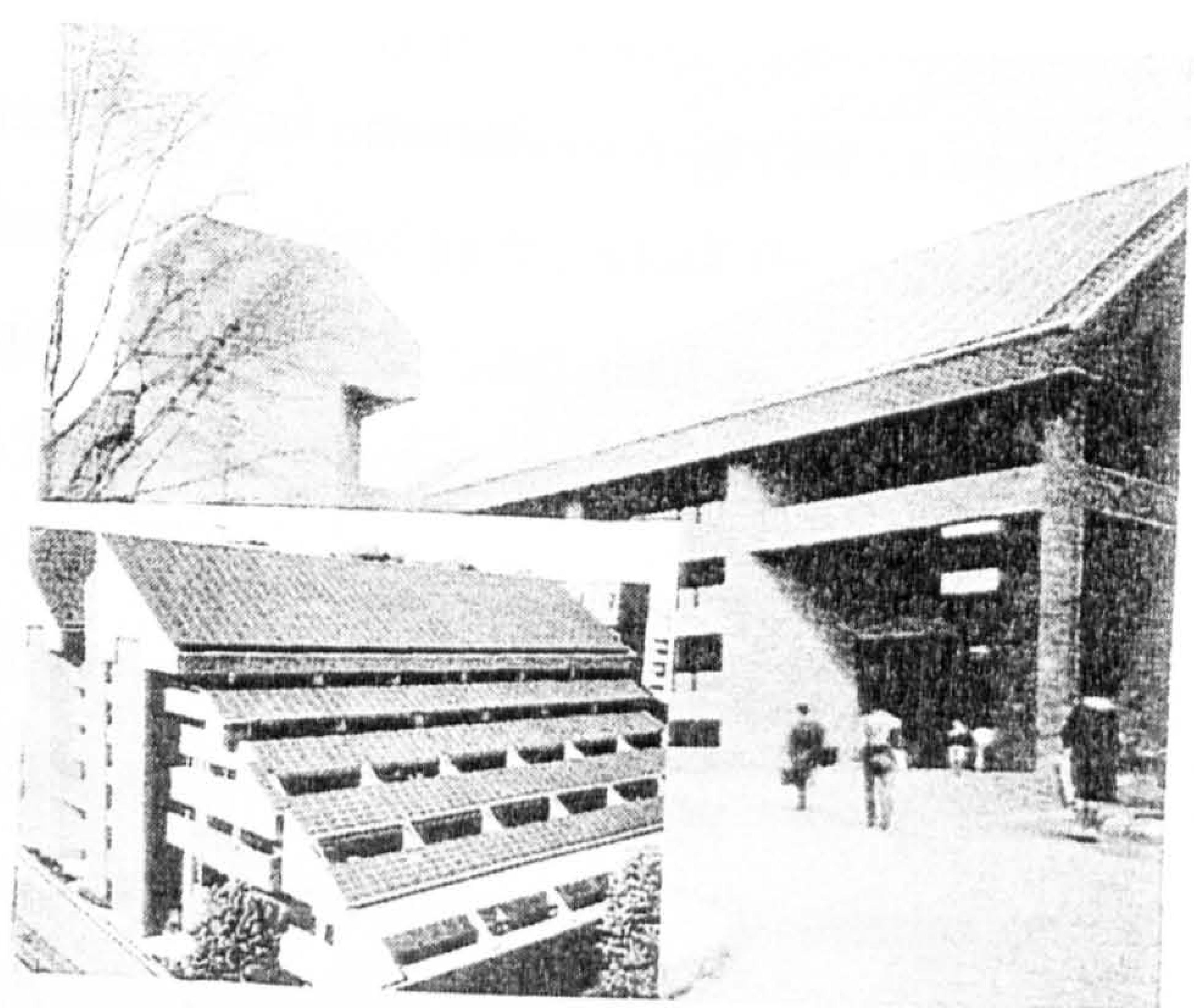
The potential of the prestige Commercial Office Building can be best illustrated by the Scheidegger Metallbau Building in Switzerland (Photograph A.13), and the Flachglas Factory in Germany(Photograph A.14). These buildings are all characterised by an expensive multifunctional curtain wall. The functions of the curtain wall include weather protection as a sunscreen or a rainscreen, aesthetic purposes, recycling of warm air and production of power. The Scheidegger system has an installed capacity of 18kWp[16] and the Flachglas polycrystalline system has an installed capacity of 12.5kWp[17]. These are small sizes, but the effect they have had in terms of operational experience and information dissemination are the very same effects that are expected from such systems in the benchmark city. Even though, the Scheidegger system contributes up to 20% of the

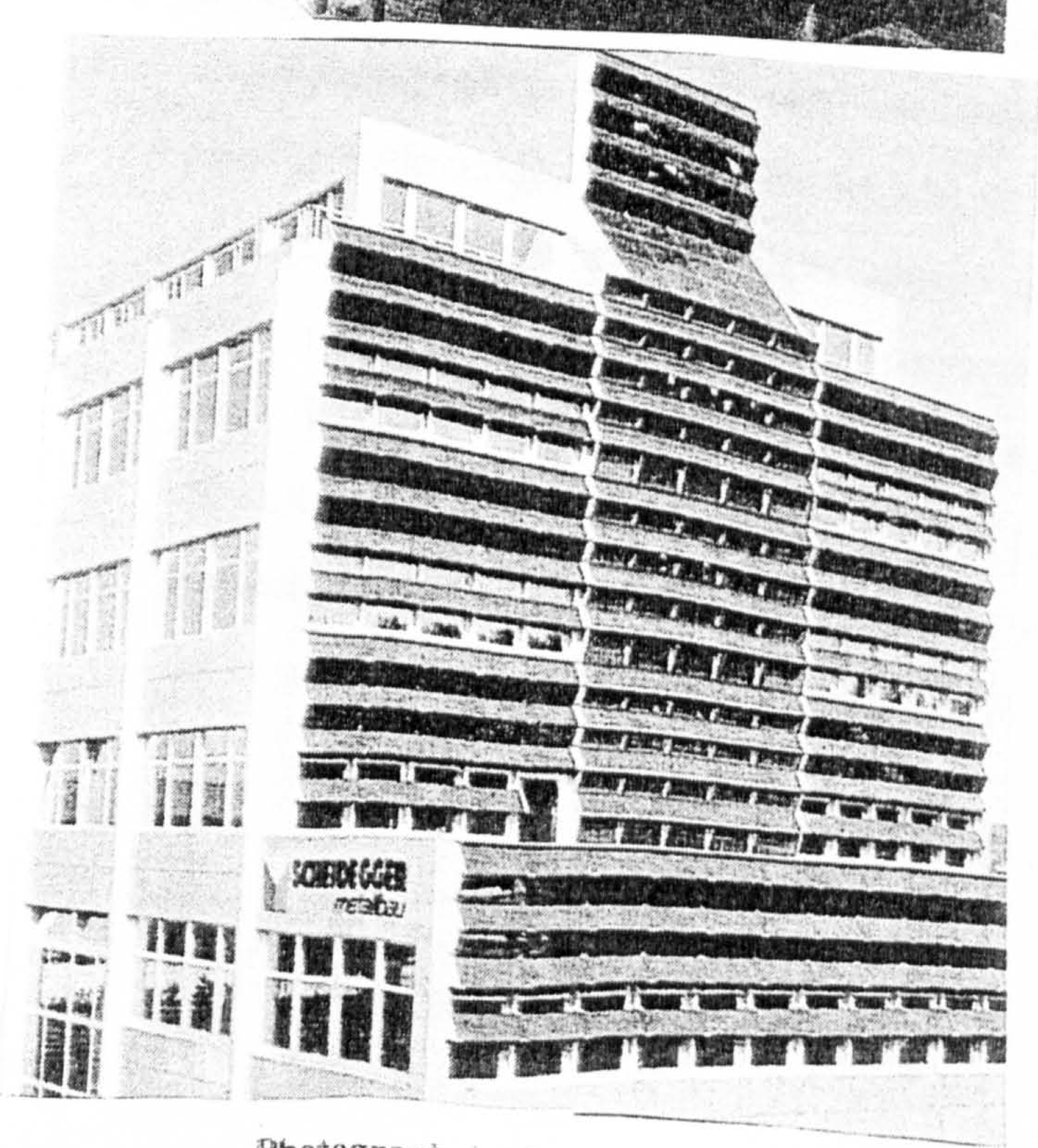
Photograph A.10

Photograph A.11

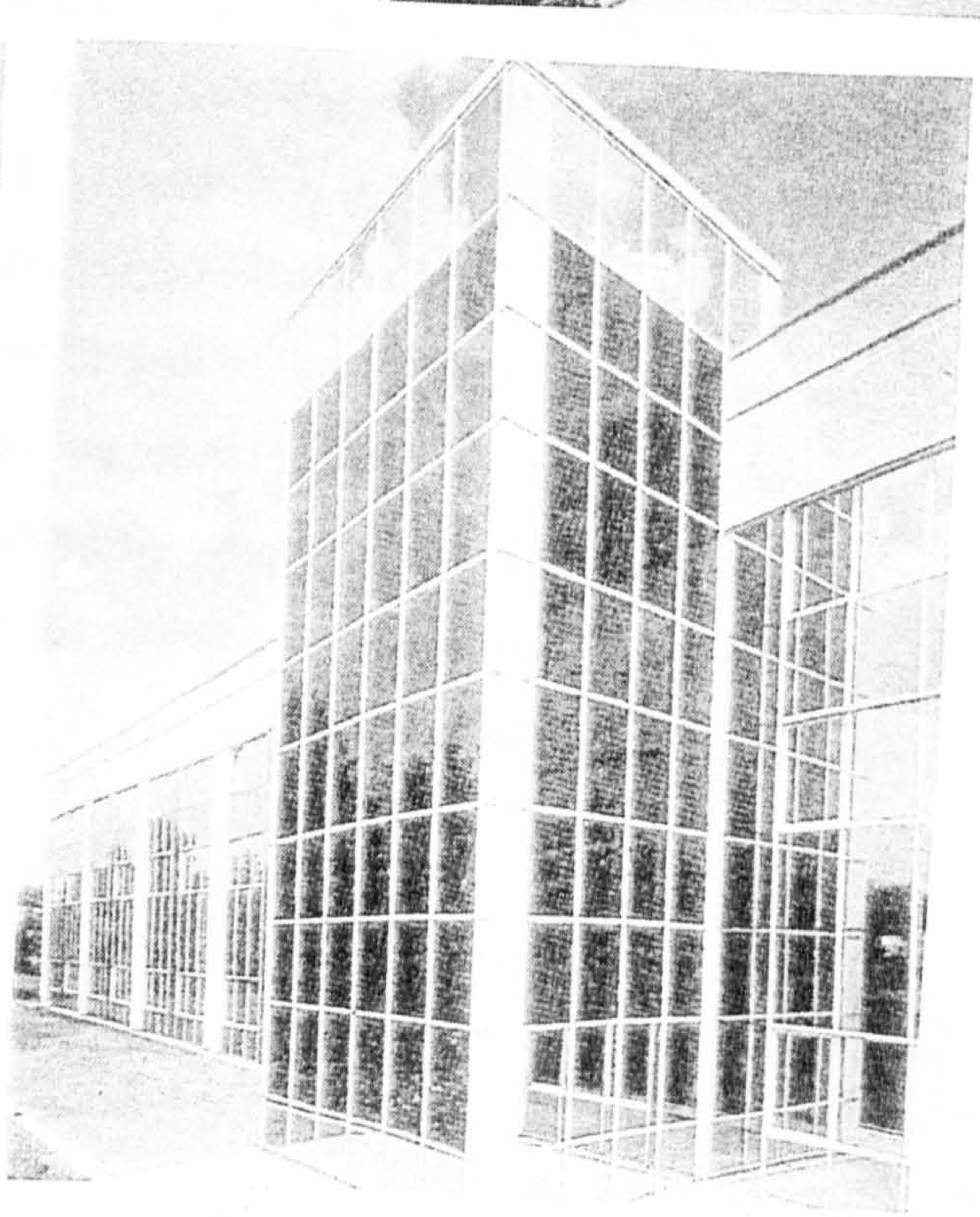
Photograph A.12







Photograph A.13



Photograph A.14

sunscreens[22]. As shading systems have become accepted architectural elements, optimising their configuration in relation to requirements and location has become important, because the systems have to offer a selective performance in order to balance the need to exclude solar radiation during overheated periods and the need to admit it during underheated periods[23]. Solar gains were traditionally limited by the masonry wall which required small and few openings, and whose mass modulated the gains. This was deconstructed by the advent of new materials, especially the concrete and steel options which made glass panes the main protective element. The deficiency in solar protection led to shading systems. Increased use of communication systems technology led to excessive internal gains, and avoiding external gains became a must. However, views to the outside and natural light were still required. Shading devices also had to fulfil aesthetic roles in addition to functional ones[24].

In the southern hemisphere, walls with north and east/west orientations may receive up to 40 and 22 times more radiation, respectively, than that received by the south face. Shading on the south face may therefore be unnecessary. Installing identical shading devices on both surfaces therefore indicate that orientation has not been considered carefully.

To prevent excessive glare all windows should have suncontrols. Variable and movable controls are often more effective in using daylight than fixed controls. The main power source that determines the thermal environment in a building is the sun. The amount of solar radiation received indoors by direct penetration of sunlight through the windows is usually the greatest source of solar heat gain. In the case of glazed windows, the sunlight can raise the indoor temperature well beyond the outdoor due to the greenhouse effect. Sunlight comprises mainly, short wave radiation to which window glass is almost transparent. The incoming radiation is absorbed by wall surfaces which in turn , emit long wave radiation. Glass is practically opaque to long wave radiation. Therefore the heat of the sun having once entered the window, is practically trapped inside. The solar heat gain through windows can therefore be excessive in the summer for temperate regions, while in the tropics it is a constant source of discomfort. The methods traditionally used to reduce solar heat gains through windows include: i) orientating the building in such a way that facades with large openings face towards the direction which receives less sunlight; ii) using special glasses which act as heat filters; iii) using shading devices such as sunscreens, overhangs, louvre systems, blinds and others in front of the windows.

Careful design of shading devices should allow the utilisation of daylight illumination, control of glare and solar heat gain. Fixed louvres are less expensive than movable ones and are appropriate for continuos sunshine. They also assist the aesthetic considerations of the building designs. However, adjustable devices can provide a flexible control which can eliminate the need for further control within the building and thereby greatly reduce the energy consumed in cooling the building. The primary data required for the design of shading devices are the values of the solar altitude and azimuth. The accuracy of the trigonometric expressions used depends on whether the shading device will be used for other purposes such as carrying photovoltaic modules. In this case, in addition to fulfilling the shading requirements, the equations must allow for the proper tracking of the sun so that the modules can be used to their maximum potential.

The design of shading device is done against a background of the requirements of occupants to have a optimum amount of sunshine entering their working environment. As a result fenestration is a synthesis of many parameters which include solar radiation control, daylight illumination, direct and reflected glare, view out of the building, the building structure and envelope[25]. Since buildings have different orientations and uses, each has its own facade design. However, the earth-sun relationship is such that it is appropriate, in the southern hemisphere, to have sunscreens on the northern facade, and closely spaced vertical louvers oriented towards the south on the eastern and western facades, and widely spaced vertical louvers at a normal to the southern facade.

General considerations for commercial buildings are as follows:

- Air-conditioning costs, including initial and operating costs can be the biggest cost items of office buildings.

- Selection of design and shape of the building envelope can influence the peak air-conditioning load by more than 30%.
- The most economic buildings have no windows on the eastern and western sides of the building and have their longest walls facing north and south.
- The cost of air-conditioning plant per rentable unit area decreases as the gross area increases.
- Total costs, including initial costs through life maintenance costs, increases as the ratio of glazing increases
- The required capacity of the air-conditioning plant is inversely proportional to sunscreen efficiency.
- There is always an economic disadvantage in placing any (horizontal) sunbreaks on the eastern and southern facades. This is because solar geometry makes horizontal sunscreens alone ineffective on the northern facade. The appropriate installation will be vertical louvres. Furthermore, for a single horizontal sunscreen to be effective on the eastern facade, the required vertical shadow angle demands it to be of very large dimensions and therefore unsightly. Multiple louvres of smaller horizontal projection would provide the required vertical shadow angle as well as a better quality of daylight illumination in the room.

These considerations have led to a wide range of models for designing sunshading devices[26]. Some of these models have been incorporated into simulation software. However the modelling of multifunctional shading features is still under development, and to consider them requires a tool which gives the flexibility of considering the roles of the shading system separately.

5.4 Modelling A PV Sunshading System

This requires modular software so that the following modules can be considered when simulating the PV sunshading system

- The Shading Component Module

- The Power Generating Module
- The Building Structure Module
- The Building Energy Load Module
- The Weather Module
- The Control System Module

The consideration of available simulation software carried out in Chapter 3 showed that TRNSYS is modular in nature and is an appropriate tool for considering a PV shading system. If the shading feature is moveable it becomes a dynamic system which has to achieve some stability for it to operate efficiently. It therefore has to have a control system, and this is usually achieved by the use of a motor. The consideration of such a tracking system can be best understood by considering the issues pertaining to PV tracking systems.

5.4.1 Concepts of Suntracking Systems

5.4.1.a Computer Control of A Suntracking System

Static placing of solar panels on the side of walls limit their exposure to the sun. This does not maximise the average solar energy they intercept during the course of the day. A computer or microprocessor based automatic tracking system is therefore necessary to control the movement of the solar panels such that they are always aligned towards the direction of the sun. As the plane of the panels is always kept normal to the direction of the sun, maximum energy can be collected from the panels. In demonstration buildings it has been found necessary for a group of PV laminates to be mechanically grouped together in a unit, so that the whole array is made of a number of units. Each of such each units can have its own tracking mechanism.

The system would operate with the computer changing the speeds of the actuators for each unit at regular intervals. Each actuator requires individual calculation of the appropriate speed, because the error in the alignment of units is usually greater than the following error. Sources of following error have to be evaluated, and, for specific data rates over the communication link between the central controller and units, the variables within the system are chosen to minimise the following error[27] Accurate sun following requires a data output of a given rate for a specific number of units. A computer based learning process can be used. This is implemented by collecting data from each unit at a given rate for all the units.

Early designs used angle encoders on the unit actuators and misalignment sensors for feedback to ensure following accuracy[28]. The path of the sun is approximated as a series of straight line segments followed by the panels. By communicating speed commands more frequently to each unit, the tracking error can be reduced, but only at the expense of an increased data rate between the central controller and the units. It is assumed that all units require unique speed commands, and with this assumption the communication requirements of the data link connecting the units to the controller are considered with respect to allowable tracking error for direct sun tracking. Both error and data rate are functions of variables within the control system, and these variables are evaluated for each data rate.

The Carden[29] system incorporates an adaptive controller which can learn certain parameters governing the behaviour of the tracker, in particular such a controller may deduce the pointing direction of a fixed axis, and also the relative direction of the other axis, the rotational axis. This constitutes a measurement of how the unit is aligned. This eliminates the necessity of an alignment procedure, and thus reduce the cost of the tracker. The controller will therefore train itself to align an array in the same direction, even though initially all units in the array were not identically oriented. The accuracy with which the parameters are learnt depends on the variables within the system, and in particular on the data transfer across the link. The variables in a possible system have to be such that the data rate is minimised.

The units can be treated as if they have orthogonal axes, which includes both altitude-azimuth and equatorial systems. An actuator on each axis allows the unit to track the sun directly. The fixed axis of the units is assumed to be in the N-S plane. Each unit has a sun sensor which gives signals related to the tracking error. The actuators are designed so that a short time after the receipt of a speed command they behave as if they have changed to the correct speed instantaneously, and no errors are accumulated. These characteristics enable the controller to determine the angular position of the actuators and thus the pointing direction of the unit by using knowledge of previous commands, and the initial position of the unit. The controller can direct the unit to follow any path in the sky depending on the structure on which the unit is mounted by giving the actuators new speed commands at intervals. The interval between the speed commands is maintained constant.

Alignment is determined by utilising the tracking error information (derived from the sun sensor) to ascertain the initial position and alignment of the unit. This is done by the unit acting like a function which transforms the input(angular position of the actuators generated by the speed commands from the controller) into an output(a pointing direction). This function is a function of the unit mechanical variables such as alignment of axes. Conversely, the unit parameters can be calculated from the knowledge of the output(pointing direction) and the input(angular position). When the unit crosses the sun, as sensed by the photosensor, the unit pointing direction is then known, as is the direction of the sun. The time and position when each crossing occurs are called the fix position and fix time respectively, and there will be a set of fix times and positions for each co-ordinate[30]. These constitute the output data. A correlation process, where a trial output set from a set of trial input parameters is compared with a true output is used.

The use of more complex control actually generates the possibility of cost reduction. The simplest physical arrangement for anticipating the sun's position would be to align the units identically, to a millirad order. This however requires regular checking and make the maintenance process expensive. The system above, however, allows the units to be installed with little attention to alignment, and their actual alignment is determined accurately after installation. The alignment may be repeated at intervals. The number of parameters governing the behaviour of a unit may be increased beyond those related to alignment. It may be cheaper to employ nonpositive drives such as belts, friction drives or winches, and in this case drive ratios may vary from unit to unit and may even vary with time. Other less expensive manufacturing capabilities may also reduce cost.

5.4.1.b The Sun Sensor

There are various ways of devising a direct sun sensing system. The most precise method is utilising the pyrheliometer[31]. This is too expensive for tracking systems involving many units. Another method uses the unit as the sensor[32]. It makes use of initiating movements of the unit at regular intervals and comparing the maximum output of the unit between the present position and the previous position. If an increase is observed then further increment is made until the output begins to drop. If decrement is observed, motion is reversed. This method is however susceptible to hunting of the unit. A novel sensor assembly consists of a differential light sensor mechanism[33] shown in Figure 5.1

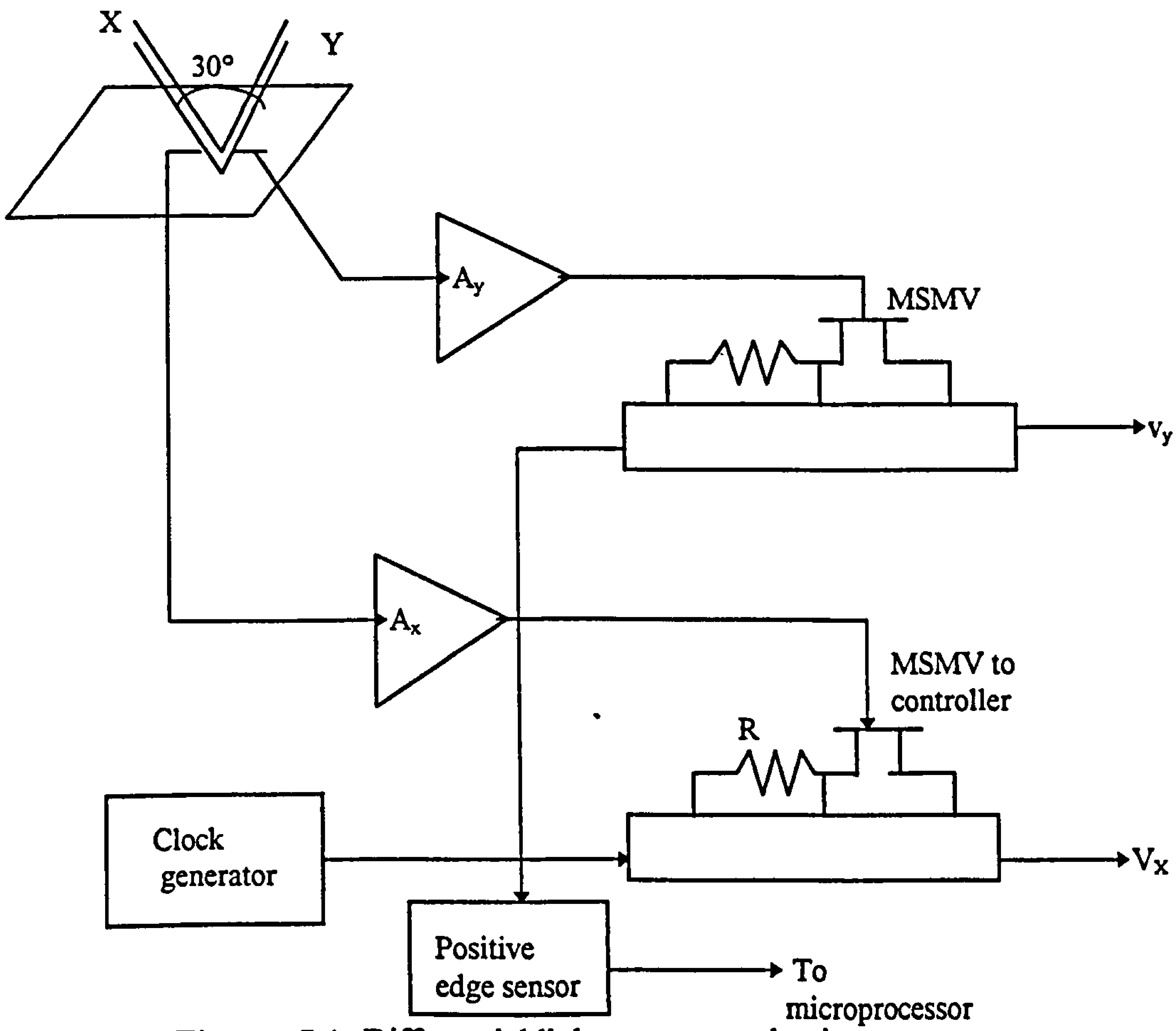


Figure. 5.1: Differential light sensor mechanism

The mechanism consists of two light dependent resistors (LDRs) fixed inside hollow cylindrical tubes thereby simulating a pyrheliometer by restricting the field of view of the light sensors. The plane of the sensors, arranged East - West, is normal to that of the unit. The differential signal representing the angular error of the unit is used to rotate the unit in such a way that the angular error is minimised. Signals from the LDRs are amplified by amplifiers A_x and A_y. If the unit is facing the sun such that the line joining the sun and the panel is bisecting the angle between X and Y, then the light intensities falling on the LDRs are equal . The amplifier outputs of A_x and A_y are therefore the same. These are used to bias 2 field effect transistors (FETs) so as to obtain equivalent capacitances proportional to the light intensities.

Each FET is included in a timing circuit of a monostable multivibrator (MSMV) as a capacitance element. This is because any gate control voltage of the FET would change the drain source junction capacitance accordingly. Therefore, any change in the light intensity would change the capacitance and hence would produce a change in the duration of the pulse generated. Both MSMVs are triggered by the same external clock generators so as to produce synchronous pulse width modulated signals proportional to the intercepted light intensities.

The controller is supported by a peripheral interface devices (PIDs)which interfaces with the signal conditioning circuits. The positive edge of the clock signal is sensed by a logic circuit and is used to interrupt the controller .This checks whether voltage pulses V_x, V_y have arrived at the controller and to start the subsequent operations. The outputs of the MSMVs are connected to the I/O port lines (e.g. PA0 and PA1 for say port A). The duration of pulses (t_x , t_y) which appear on these lines are determined in the controller by running software counters. The count difference (n_x - n_y) is multiplied by factor K for generating longer duration pulses to drive a DC motor. The DC motor is gear coupled to the panel such that it would rotate the panel in the East - West direction. Pulses with increased duration are placed on selected lines of another I/O port B, depending on whether the count difference (n_x - n_y) is positive or negative. If positive, it would appear on line PBO, otherwise on PB2. A pulse signal rotates the motor in a clockwise direction and that at PB2 anticlockwise. The motor rotates proportional to the duration of the pulse sent from the controller.

The apparent speed of the sun is very slow. Thus, the panel is rotated only during the generation of the time difference(t_x - t_y) of the MSMV output pulse. A repetition interval can be chosen for the external clock pulses. Then during each interval the controller checks the time difference (t_x - t_y)and stores this as a count difference (n_x - n_y). Duration (t_x - t_y) is proportional to the intensity difference received at the LDRs (X, Y). If X receives more light intensity than Y, then ($t_x > t_y$) and the controller generates a pulse with width proportional to (t_x - t_y). This pulse rotates the motor until the intensities become equal. Since equal intensities give (t_x - t_y)=0 no pulse is generated. When the sun moves to another position, slightly different from the previous one, then (t_x - t_y)>0, and the next pulse is generated . The motor moves again and the whole operation repeats itself from sunrise to sunset. The detection of the difference in light intensities depends on the sensitivity of LDRs. Due to atmospheric conditions and diffusion of white light in the atmosphere, it is difficult to detect the sun movement of much smaller angles.

If n_x and n_y are the software counts made for the light intensities received at X and Y respectively, the width of the pulse generated by the controller for driving the motor would be (n_x - n_y) x N where the N is a factor determined by the response time of the motor and the gear reduction mechanism. If 1 count corresponds to n_c clock cycles of the controller , then the pulse width in terms of controller clock cycles is

$$(n_x - n_y) * N * n_c \qquad (5.1)$$

As the sun traverses from east to west the panel rotates following its motion. There are 2 limit switches attached to the panel to mark its maximum angular position in east and west directions. The status of the limit switches are read to the controller over port lines and a 1 at the port indicates that the maximum angular position in West direction has been reached and the panel should not be driven any further. The panel must be rotated towards the east to make it ready for operation on the next day. This achieved by sending a high signal over the line continuously until the east limit switch is sensed. During night times there would be no signal from the sensors as light intensities on the sensors would be low and therefore equal.

The controller, while issuing the signals to PB0 or PB2 looks for the status of the limit switches over the PCO and PC1 lines to avoid the turning of the motor beyond limits.

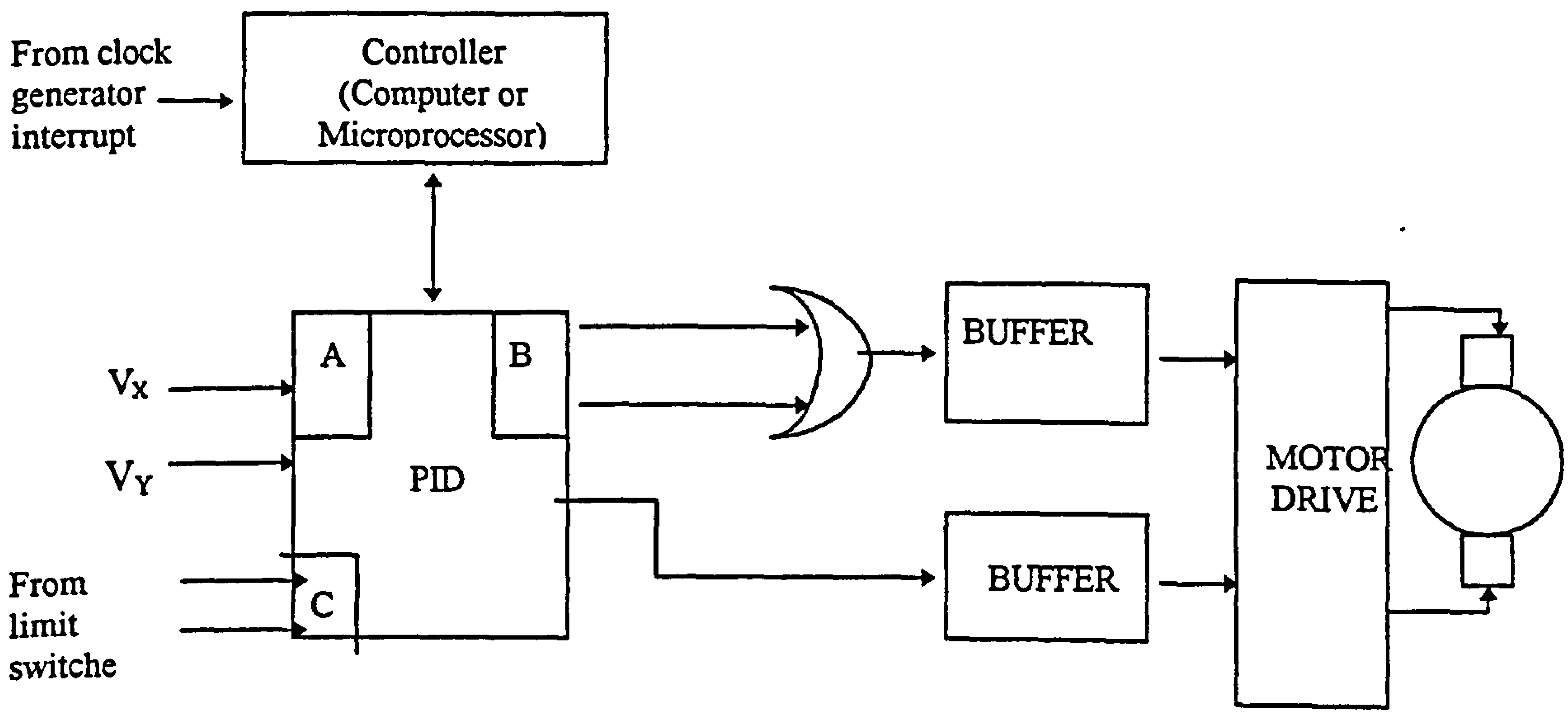


Figure 5.2:Block Diagram of The Control System

For an array with many units such an arrangement would involve the use of a multiplexing system whereby each unit is polled for the transfer of control commands over the communication link to the controller.

5.4.1.c Digitisation

The flow of information over the communication link helps to determine the feasibility of the scheme. It requires digitisation of the data to preserve accuracy and minimise costs, and this causes certain discretisation errors. The small size of the photosensitive elements of the sun sensor imply that providing the error is smaller than half the angle subtended by the sun, analogue signals varying nearly linearly with the pointing error can be assumed. These error signals are digitised into a binary number of n_s bits, and the full intensity of the sun gives a sample of 2^{ns}-1.

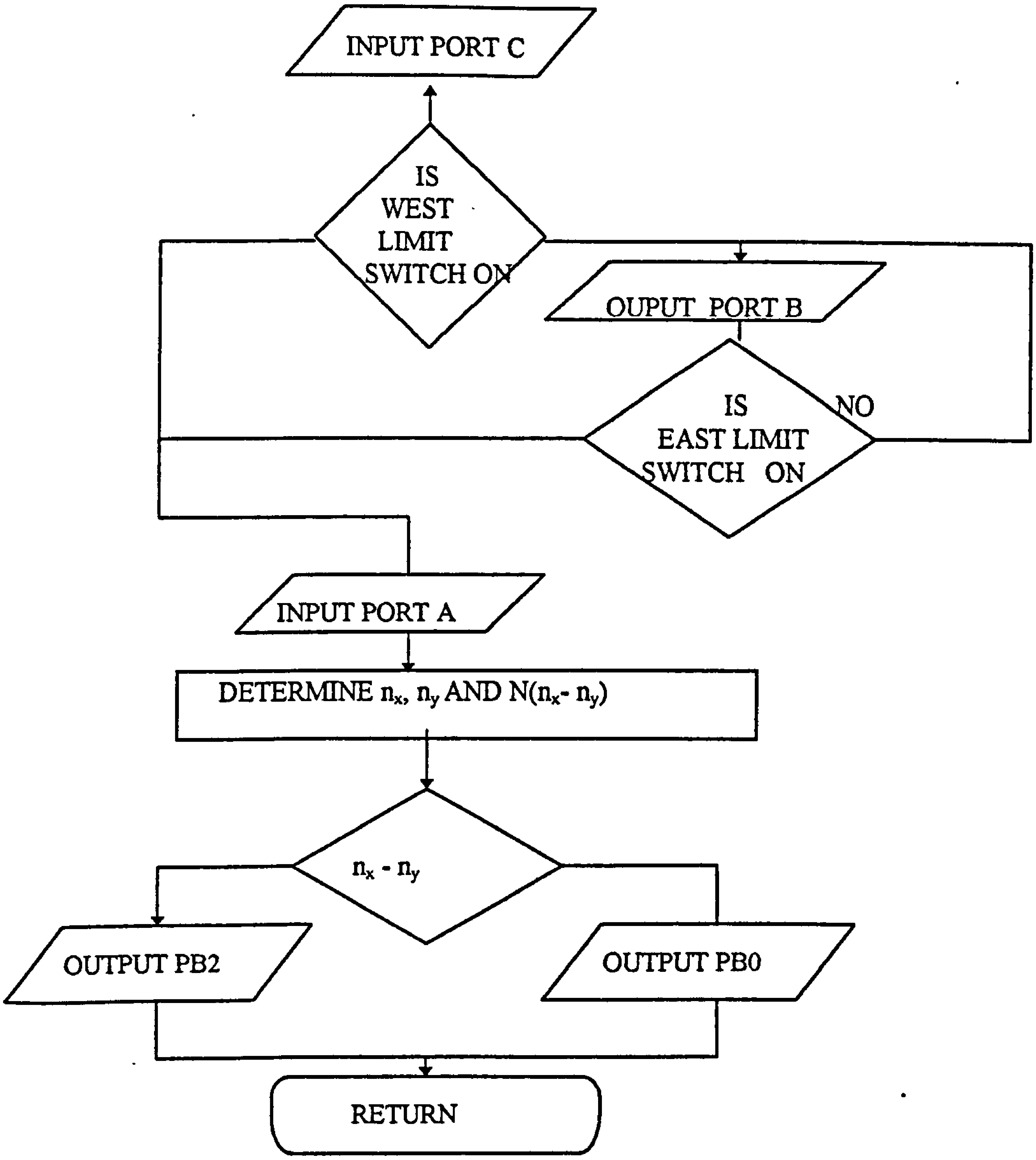


Figure 5.3: Flow Chart for Sequential Control Operation

Thus the maximum error of the device at small tracking errors (under 0.005rad) is:

$$\Delta\theta_s = \frac{\Omega}{2(2n_s - 1)} \tag{5.2}$$

Ω = solar diameter Three parameters are required from the sun sensor. The third is the representation of the intensity of the sun, which determines the validity of the two error signals. The command speeds to the actuators are also digitised and only one set of discrete speeds is possible. There are (n_m+1) bits in the speed command, the extra bit being the direction of the speed, and the maximum speed change is given by:

$$\Delta(\Omega) = \frac{\pi}{T2^{n_m}} \qquad (5.3)$$

T is the traverse time (for π rads).

The data rate over the communication link and the controller and units can be divided into two parts, the motor speed commands leaving the controller, and the feedback information returning from each unit to the controller. A message to each unit is unique and therefore needs an identifier, which in this case is a binary number. For 100 units 7 bits are required for this identifier. The 7 bits are attached to each message. Thus the data rate for the command is :

$$R_m = 100(7 + 2(n_m + 1)) / t_c \quad \text{bits/s} \qquad (5.4)$$

5.4.1d Determination of Pointing Accuracy

The sources of error during sun following are

- The segmented straight line approximation to the sun's path.
- The discretisation of motor speeds
- The accuracy of the determination of the unit parameters referred to previously, which is carried out by a correlation routine.

•Errors due to segmented line fit

The path of the sun is assumed to be given by the equations derived from a uniformly rotating earth, with the declination of the sun varying sinusoidally with time (2). The tracking errors in this case come from two sources: a) errors produced by approximating the sun's curved path as a series of straight line segments; and b). errors due to the unit falling behind the sun due to the sun's azimuthal velocity near the zenith. This high velocity has a maximum of (2):

$$\dot{\phi}\ (\max) = \frac{k\cos(d)}{\sin(B - d)} \qquad (5.5)$$

where b is the angle between the azimuthal axis and the equatorial plane, k is the rotational velocity of the earth, and d is the solar declination.

The strategy for calculating a path closely approximating the sun's in either co-ordinate is as follows. For the first constant speed interval, the path is an unconstrained linear least squares approximation to the path of the sun. For subsequent intervals a linear least squares approximation is used with the constraint that the starting point must coincide with the endpoint of the previous interval.

• Motor speed discretisation error

The discretisation of motor speed commands causes a second degradation in accuracy. Generally, it is impossible to arrive at a specific position after a certain period of motion, because one is forced to choose a speed which is slightly in error with respect to desired speed[24]. The positioning error at the end of time t_c is called the discretisation error and is given by:

$$\Delta\theta_2 = \Delta\Omega \cdot \frac{t_c}{2} \tag{5.6}$$

• Error due to correlation process

In order to implement sun following the controller requires knowledge of the sun's position, and knowledge of the response of the unit to speed commands in terms of pointing direction. This knowledge involves the unit parameters e.g. the pointing direction of the fixed axis, the initial pointing direction, and so on. To allow for flexibility, and the possibility of cost reductions, 7 parameters are considered, including 2 angles to describe the lean of the fixed axis, 2 angles to describe the initial position of the unit, two numbers to describe the gear box ratios and a final parameter describing the angle between the two axes of rotation. These parameters relate to the alignment and construction of the tracker to the local alt-az frame.

The accuracy of sun tracking depends on the accuracy of determination of the tracker parameters, which in turn depends upon both the accuracy of the fixes collected and the number of fixes. The ratio of the pointing error due to imperfect knowledge of the unit parameters to the fix error (error ratio) is important. It is independent of fix error as expected. Its value is determined from a series of simulation runs.

Statistically, it is realised that the correlation process has to be carried out over the full range of the input and output variables i.e. over a minimum length of one day. With a typical set of parameters, an artificial set of fix positions for one day can be created with a specific fix error. A minimisation routine then evaluates a tracker parameter vector which correlates best with the artificial set of fixes. Using knowledge of the original set of parameters used to generate the artificial set of fixes, the pointing error due solely to the inaccuracies in the determination of the estimated set of parameters can then be calculated. The error ratio is then calculated. The ratio is found to decrease with increasing numbers of the fixes. The graph of the expected value of the ratio is a straight line of negative slope, but upper boundary of the points(the variation encountered) is an exponential decay with points always higher than corresponding ones on the expected curve as shown below
The contribution to pointing error is given by the product of the error ratio(r) and the fixed error $\Delta\theta_f$ i.e.

$$\Delta\theta_3 = r\Delta\theta_f \tag{5.7}$$

The fix error depends on the system used to collect the fixes.

5.4.1e Summary

The possibility of implementing the sun following scheme depends on 2 factors: the ability of the communication network to handle the necessary data rates and the ability of the central controller to perform the required computation. The data rates calculated by previous researchers show that this is no barrier.

The computation can be divided into two major items. The first is the necessity to calculate speeds for every one of the units each command time t_c, and thus each calculation must only take t_c divided by the number of units. This is not demanding constraint for modern day controllers. The second item is the computation required for the correlation process, for which every night is available. Numerous correlations could be performed per night and a correlation for every unit could be done at regular intervals say weekly. The control system can be shown below

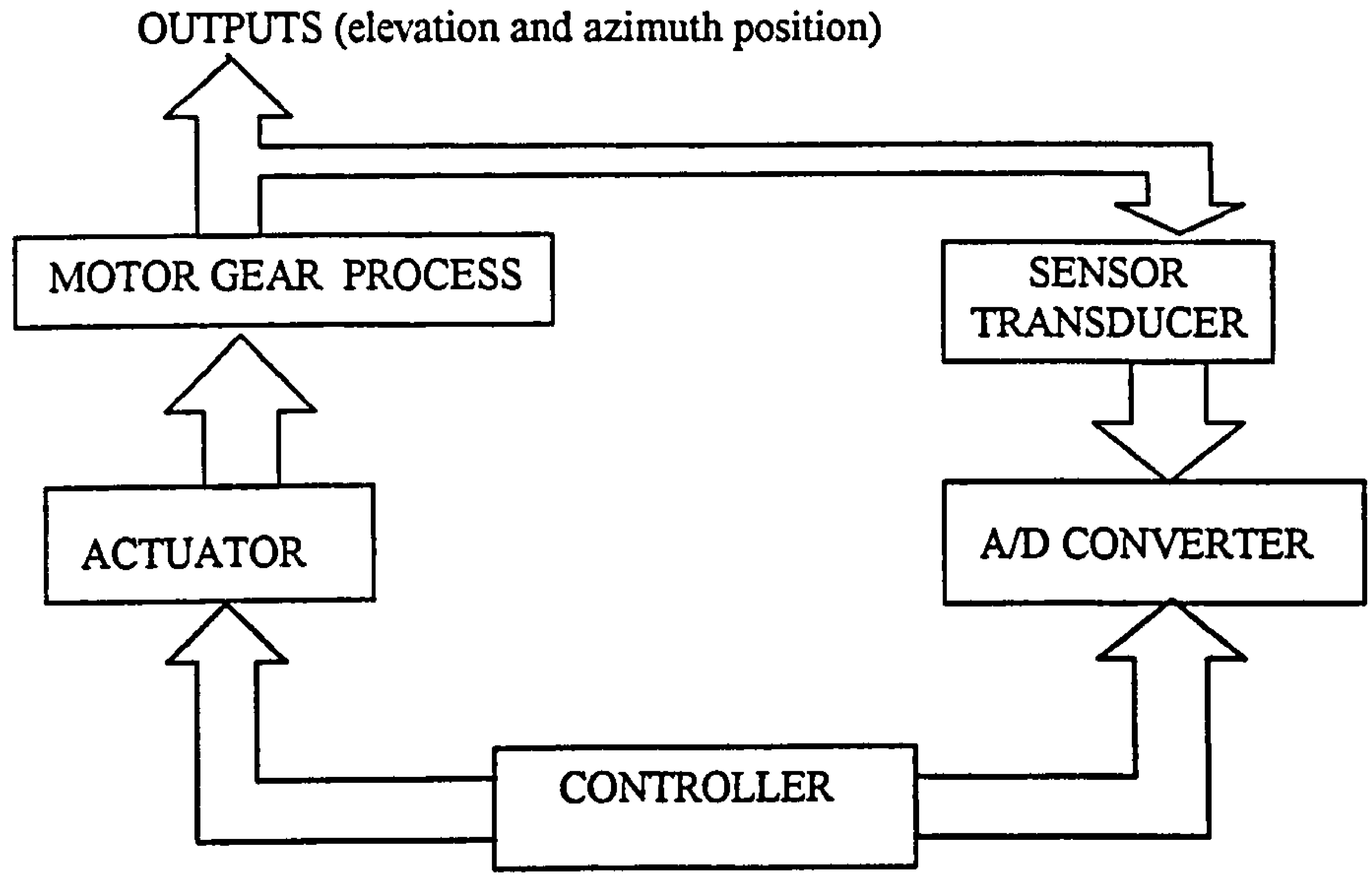


Figure. 5.4: Closed Loop Control System[34]

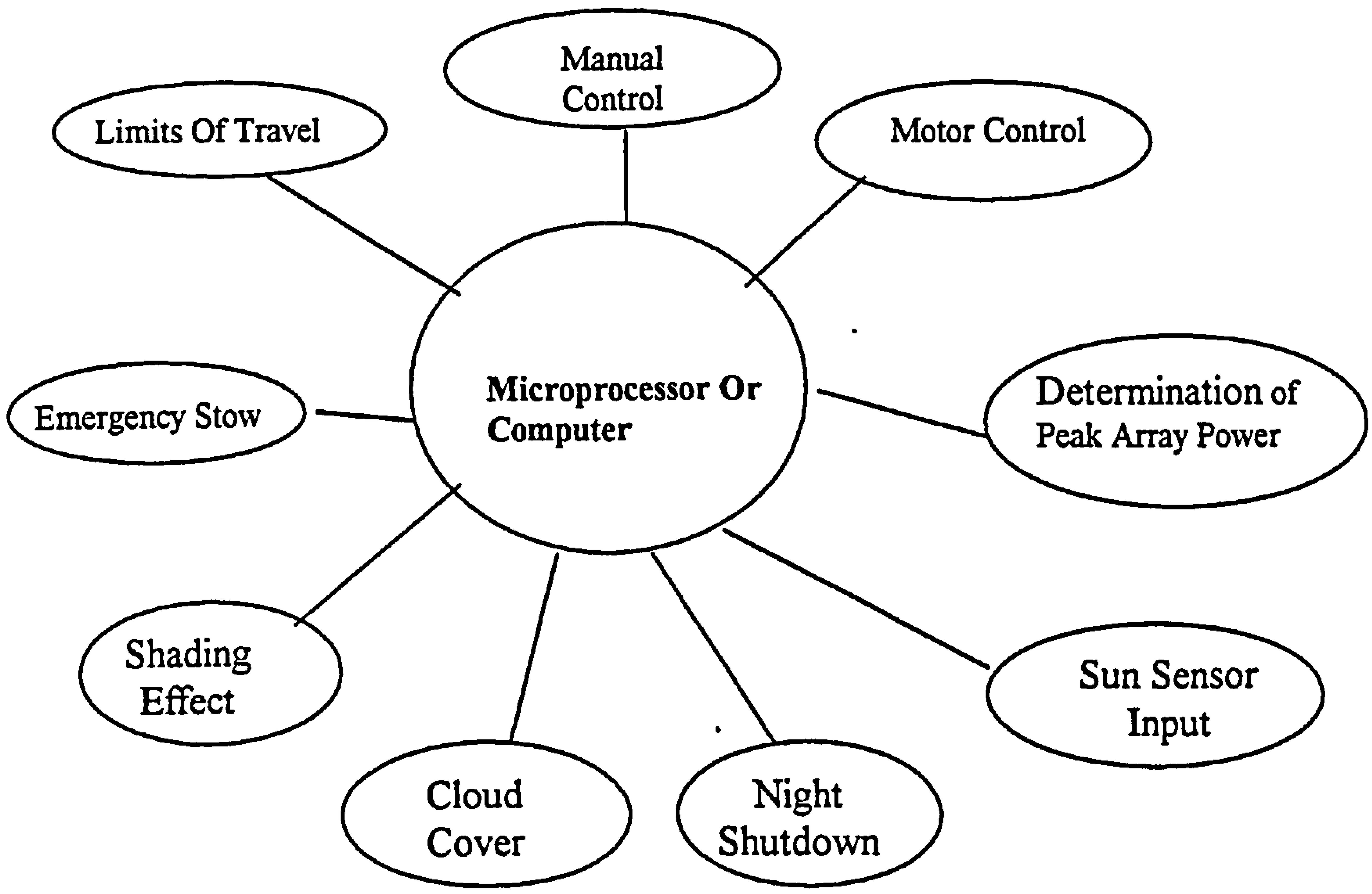


Fig 5.5: Software Functions Of Controller

5.4.2 Constant Self-Learning Scheme For A Tracking System

A tracking system is affected by defects and deviations which include: misalignment of the tracking axis; flexion of the structure under its own weight; torsions and deformations due to loads of varying directions as the system turns[35].

The system must correct the errors without knowledge of the precise value, and with a given tracking accuracy, for example <0.2°. The system output is usually the parameter that is optimised. Therefore, the system adapts itself to changing errors and drifts of any of its elements. Some tracking systems learn a limited set of misalignment parameters at start up, when they scan portions of the sky looking for maximum output from the array. The collected data that is used to calculate the set of parameters that fits best the aiming error can be found by using the least square methods or other similar estimating methods[36]. The parameter usually the misalignment of the rotation axis although others can be incorporated. Once the starting up stage is accomplished, the system starts tracking with the parameters learned, correcting the aimed position with the misalignment and offset found for each tracking axis. The set of misalignments remain unchanged until a new start up is done. This assumes misalignment errors are precisely determined at starting up and that errors are constant with time.

The conventional approaches to self-aligning systems have two major constraints which include: i) only misalignments observed at start up are learned, thus drift of any form, such as clock drift, mechanical drift or others, adversely affects the aiming of the system; ii) sources of error which are defined solely by the designers' criteria, exclude other error sources not included by the designer's definition from being corrected.[37] A good system should correct continuously in operation, regardless of the origin of the error. Algorithms based on a dynamic table of angular corrections which is continuously updated can be used. Each value in the table is related to the angular range required and to a confidence variable. The confidence variables determine how the angular correction is updated with the observed data.

The starting point to determine the misalignment of the tracking axes in double-axis solar tracking system is characterised by pairs of values for azimuth and elevation. These are resolved by solving the system of equations linking the least squares estimates of misaligned parameters with the pairs of values[36]. Single-axis tracking systems are however, more difficult because the starting points are defined by single-values. The tracking strategy assumes all misaiming errors to be in a table with the first column consisting of values of the angles towards which the system is to be aimed at, and the second column consisting of the estimates of error that the system introduces for such angles.

The correction angle is denoted by $[\kappa] = \{\kappa_i^{(-(m-1))}, \kappa_i^{(-(m-2))}, \ldots, \kappa_i^{(m-1)}, \kappa_i^{(m)}\}$

- where $\kappa_i^{(m)}$ is the correction and error estimate associated with the tracking range between m-1° and m°
- i which indicates the position of the dynamic character in the table increases with each movement of the system as it moves in steps (driven by a motor). Thus a tracking range of ±45° is represented by a table with 90 values where 1 value/degree is enough to characterise the system. To aim a system at n° the expression

$$\omega_i = \Omega(t) + \kappa_i \tag{5.8}$$

where $\kappa_i = \kappa^{(n)}$ is the error estimate associated with the angle where the system is currently positioned and ω_i is the angle describing the expected position of the sun. Each movement of the array provides an observation of the position of the sun which is indicated by the current output from the array. The position where the maximum current occurs shows the direction of the sun. If while the system is moving to another position the maximum current is found at an observed angle $\tilde{\omega}_i$ at moment t` then an estimate (observed) error can be given by

$$\tilde{\kappa}_i = \tilde{\omega}_i - \Omega(t') \tag{5.9}$$

Two options are possible for the movement of the array to the next position:

i. if the observed estimate is unreliable, it is ignored and the next movement is performed assuming the former estimate and making $\kappa_{i+1} = \kappa_i$, else

ii. the observed estimate is preferred such that $\kappa_{i+1} = \tilde{\kappa}_i$

These options correspond to the open and closed loop control approaches respectively. The closed loop option, $\kappa_{i+1} = \tilde{\kappa}_i$, subjects the system to all disadvantages associated with such a tracker. Thus, if $\tilde{\kappa}_i$ is affected by some noise, the tracker will be aimed at a wrong angle. Sometimes no observation will be possible to define and $\tilde{\kappa}_i$ is undefined. In general, the observed maximum current detected is validated against a threshold, whereby under cloudy conditions no observation will be valid. Choosing the open loop system means the tracking system never learns how the array is performing and therefore the misalignment errors will be impossible to correct. A compromise is the best solution. Assuming the error estimate is updated as below

$$\kappa_{i+1} = \rho_i \kappa_i + (1 - \rho_i)\tilde{\kappa}_i \tag{5.10}$$

If $\rho_i = 0$ or $\rho_i = 1$ then the closed and open loop are used respectively. A new estimate is made from the weighted average of the previous and the present (observed) estimates. ρ_i is a measure of the confidence in the certainty of the error estimate $\tilde{\kappa}_i$. If ρ_i =1, the certainty is maximum and estimate $\tilde{\kappa}_i$ is preferred over any other observation. If ρ_i =0, the certainty is minimum and the observed estimate is preferred to $\tilde{\kappa}_i$. ρ_i determines the speed at which the observed error is assimilated by the error estimate of the system. Assuming $\kappa_0 = 0$ and $\tilde{\kappa}_0 = 0$ and the system changes such that the next observed sun position is found F degrees further than expected then $\tilde{\kappa}_i$ = F for i>0 from equation 5.10. The error estimate then changes as follows

$$\kappa_{i+1} = F(1 - \rho_i^i) \tag{5.11}$$

Therefore κ_i converges exponentially towards F with time constant $1/\rho_i$. The parameter ρ_i is not static but changes with time, adapting dynamically to the changes of the system. The certainty table is $[\rho_i] = \{\rho_i^{(-(m-1))}, \rho_i^{(-(m-2))}, \ldots\ldots, \rho_i^{(m-1)}, \rho_i^{(m)}\}$ where every value is associated with a counterpart in the correction table. $\rho_i^{(m)}$ changes with time and depends on the availability of observations. The availability is not identical over the range of tracking because the weather is variable over the course of a day. The certainties are updated to represent the actual confidence on an estimate κ_i. Assuming a good estimate of $\tilde{\kappa}_i$ and certainty of its accuracy as it is obtained by averaging a large number of observations. Equation 5.10 can be seen as a moving average of incoming observations. The more observations processed the better the estimate and the higher the level of confidence on it. Therefore the level of confidence on an estimate increases with every new observation. However, with such a good estimate, if no new observations are made continuously, the actual system error will depart from the considered estimate with time. Therefore the certainty in the estimate should be decreased for each movement where the observation is not valid. There are many ways to update ρ_i, the simplest way is to consider the expressions:

$$\rho_{i+1} = (1-D_h)\rho_h + D_h\rho_i \quad \text{and} \quad \rho_{i+1} = (1-D_l)\rho_l + D_l\rho_i \qquad (5.12)$$

for movement with or without the valid observations respectively. ρ_h and ρ_l are the maximum and the minimum values the certainty can take. K_h is a learning constant and it determines how fast ρ_i converges to ρ_h. K_l is a relax constant and determines the speed of convergence to ρ_l in the absence of valid observations. Equation (5.10) has the same form as equation (5.11) thus all evolution of ρ_i towards ρ_h or ρ_l are exponential. Equation (5.11) implies that the system moves between two extreme states: closed loop and open loop. As the system learns with incoming observations, confidence rises and the system starts to behave much more like an open loop system[38]. This agrees with the fact that the estimate κ_i will be very good, and probably more reliable than the incoming observations which may have noise or suddenly become undefined due to clouds. If there is no observation to update the error estimate, the system will start to forget what it has learned or, at least, to consider its learned data unreliable. It then tends to a closed loop system as more significance is given to any unusual observation than to its old estimate.

The system should avoid going into a pure open loop mode because this reduces its ability to adapt to any drift or misalignment. The system should always be able to learn, so it can be assumed that $\rho_h < 1$. A system with $\rho_l = 0$ is acceptable, therefore it can be considered that $\rho_l \geq 0$. The choice of ρ_l, ρ_h, D_L and D_H determines how the system behaviour varies with time. The choice depends on a set of criteria which has to be developed dependent on the system requirements. The use of a closed loop implies that the system scans around the sun position, and this should be minimised in time. This makes the learning process faster than the forgetting process. Alternatively, it may be desirable that most of the time the system acts as a corrected open loop with certain feedback ($\rho_t = \rho_h$). The tendency towards this is therefore maximised while the reverse is minimised. A set of formulae is then used to determine the parameters from the required performance specification.

The observations are obtained by detecting the point where the array passes through the sun position(a point of local maximum current). The observation is only valid if the current output is higher than a given threshold. It is normal when a rising current occurs when the array is moving towards the sun position and vice versa. Hence, it is advisable to scan around the sun position by moving the array to a reference angle, $\omega_R(i)$ given by

$$\omega_R(i) = \omega_i + \delta_i \tag{5.13}$$

where δ_i is an oscillating series. This ensures that the system is moving around the expected sun position, ω_i. When the confidence in the expected sun position is high ($\rho_t \approx \rho_h$) the scanning amplitude should be small. On the contrary it must be maximum for $\rho_t = \rho_l$ as at this state the knowledge of the position of the sun is lower. Thus, it is very useful to define the oscillating series δ_i as:

$$\delta_i = \Delta \frac{\rho_h - \rho_h}{\rho_h - \rho_l}(-1)^i \tag{5.14}$$

The same exponential rise and decay of ρ_t is imposed to $|\delta_i|$. The movement of the array is done by switching on and off a motor. The motor is switched on in the appropriate direction whenever the following condition is fulfilled:

$$|\omega_R(i) - \omega_T| < \omega_h \tag{5.15}$$

ω_T is the actual tracker position and ω_h is the angle of hysteresis. This angle is actually the maximum allowed error between tracker position and reference angle. As soon as this equation is fulfilled the array is moved to $\omega_R(i)$. This switching strategy makes the system move forward only(sun following movement) whenever $|\delta_i| < \omega_H/2$. If $|\delta_i| > \omega_h 2$ an oscillation is imposed on the system which is reflected by physical scanning around the sun position. Therefore, in the steady state when ρ_i is close to ρ_h the scanning oscillation is observed, but when ρ_t is close to ρ_l the array will physically scan the sun position. Since $D_h << D_l$, the amplitude of oscillation decreases rapidly and ends up being masked by the hysteresis angle ω_h. The scanning state is needed to quickly lock the position of the sun. This state last for a very short period and the losses due to misalignment during the scanning are negligible. The scanning is masked when the level of irradiation is not enough to provide a valid observation. This is done by making $\delta_i = 0$ whenever the detector detects a poor irradiance level. In the steady state the system will regularly move an angle ω_H degrees and if the level of irradiance is enough, will detect the precise position of the sun within this ω_H angle. These observed positions continuously update the error estimate of the system, as the system learns continuously while in normal operation.

Equation 5.15 in a steady state with $\rho_i \approx \rho_h$ would lead to an average shift of $0.5\omega_h$ between ω_T and the sun position. To maintain good aiming accuracy of the array it is preferable to change (Equation 5.13) such that:

$$\omega_R(i) = \omega_i + \delta_i + 0.5\omega_h \tag{5.15}$$

The tracking system clock signal is obtained from the controller(computer or microprocessor) clock synchronised after short time intervals. An exact reference can be extracted from a GPS(global positioning) system which is presently the most reliable way to have a clock signal[40]. The motor can be driven through a set of thyristors triggered by the control board which receives direction orders from a controller. Once started, if the day is sunny, the system begins to scan around the sun position looking for the maximum current. The amplitude of scanning decreases as the system learns the optimum position until the oscillation is masked by the hysteresis angle, after which the system tracks normally. If the weather turns cloudy and less observations are possible, the certainty in this subinterval decreases and the amplitude of scanning starts to increase. This amplitude can reach again a point where it causes physical oscillations. The alternating switching forward and backwards of the motor is avoided unless the sensor detects a good irradiance level. The scan will collect valid observations, certainty will rise and the amplitude of scanning will fall again until it is masked. Therefore physical scanning only occurs when the system requires it to ensure the maximum current point is kept locked. The scan time is usually less than 1% of the total tracking time for an average sunny weather.

5.4.3 Simulation of A Tracking System

These considerations can be taken into account by first considering the tracking system for a building-integrated photovoltaic system shown below in Figure 5.6. It has already been mentioned that the best choice of a photovoltaic system would one consisting of parallel rows of photovoltaic panels which form sunshading louvres above the windows of the building on whose facade they will be mounted. The panels in each row are set on frames which lie on a joint torsion tube turned by the action of an electric motor so that they rotate about a single horizontal axis. The rotation of this platform is controlled by a vertical stainless steel arm mechanisms which can extend over the height of the building. Therefore, the rows of photovoltaic louvres rotate through the same angle in response to the changing position of the sun.

The tracking system therefore consists of a mechanical load comprised of the weight of the modules, the frames, their supporting arms and the vertical steel mechanism; an actuator system made of an electrical motor, its controller and a sensor system which senses the position of the sun. The system can be simulated using control system simulation software such as MATLAB. The control system is then centred about the suitability and stability of the moving parallel units of photovoltaic panels through a set of angles as they track the sun. The output of this simulation is a series of angles indicating the position of the tracking system at different times. This output has to be incorporated into TRNSYS.

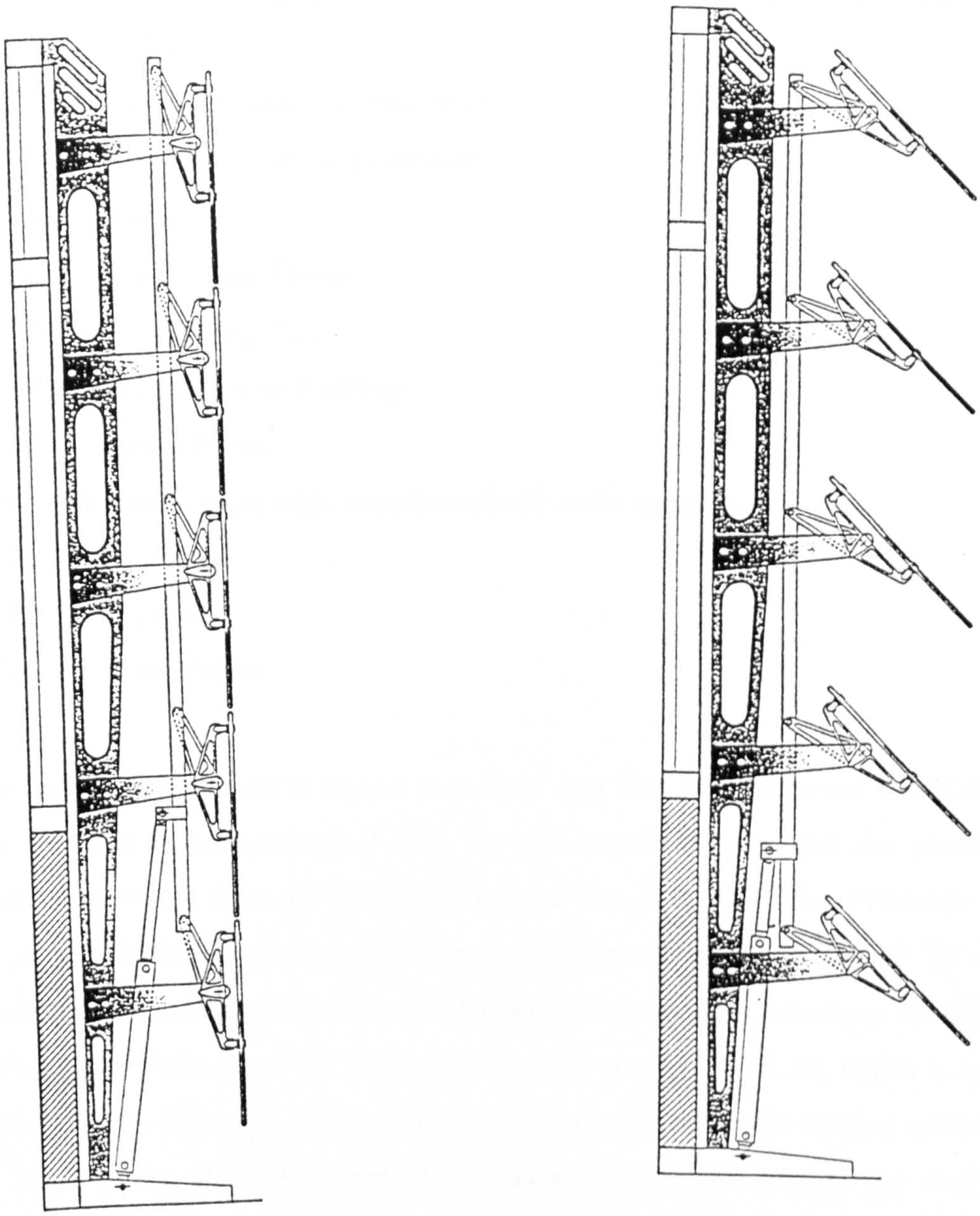


Figure 5.6 Photovoltaic Sunscreen Mechanism[41]

5.4.4 Simulating The Building and PV System in TRNSYS

The following standard TRNSYS components have to be considered for modelling the effect of a PV sunshading system on the thermal environment inside a building.

TYPE 9: The Data Reader

TYPE 16: The Solar Radiation Processor

TYPE 40: On/Off Differential Controller

TYPE 3 Fan or Pump

TYPE 51: The Cooling Tower

TYPE 52: The Cooling Coil

TYPE 56: The Multizone Building

TYPE 65: Online Printer

These additional components were formulated in the research

TYPE 71: PV Array

TYPE 72: Sunscreen

TYPE 75: Power Node

The Data Reader is used to import data from data files external to the TRNSYS suite. In this case this is meteorological data for the benchmark city and the position of the sunshading system from the MATLAB output. The Solar Radiation Processor calculates the solar radiation incident on surfaces of different orientations. TYPE 72 component simulates the shading effect of the sunshading system and also calculates the effective area of the photovoltaic array. TYPE72 is formulated around TYPE 34, which is intended for fixed shadings. However, it can be made to simulate a moveable shading system by using the angle of the shading system to modulate the effective size of the overhang. The simulation of the photovoltaic system required the formulation of another component Type71, which is based on a single diode equation method of simulating the solar cell, as explained in Chapter 2. The building structure is described in a building description file which is then incorporated in TRNSYS as a TYPE 56 component, while TYPE 2,3, 40, 51 and 52 are used to simulate the air-conditioning system.

The flow diagram of an air-conditioned building with a photovoltaic array on it is modelled in TRNSYS is shown below in Figure 5.6

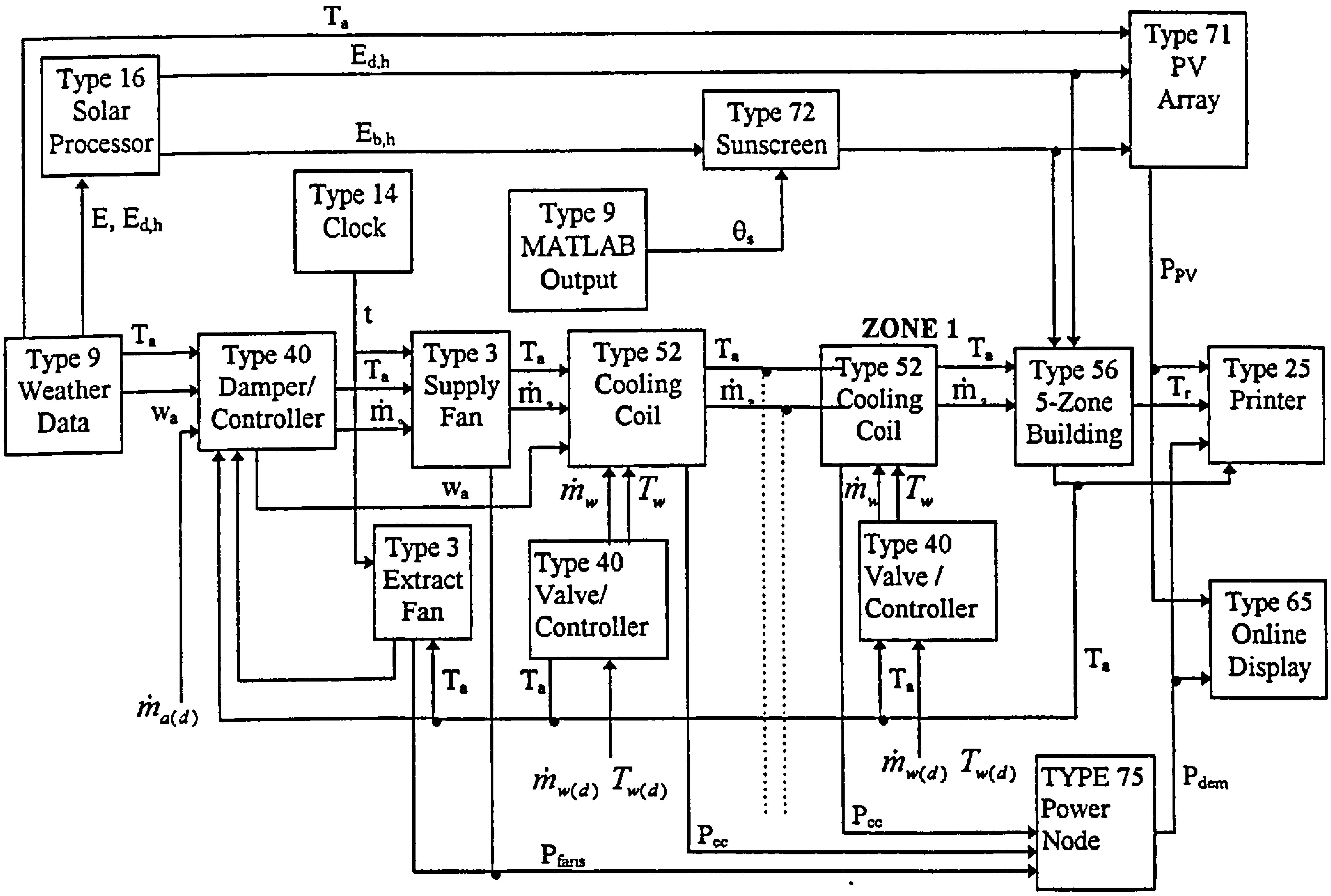


Figure 5.6: Flow diagram of an air-conditioned building modelled in TRNSYS

where

P_{PV} is the photovoltaic power generated, E is the total horizontal solar intensity, E_{dh} is the diffuse solar intensity, E_{bh} is the horizontal beam solar intensity,

P_{dem} is the power demand of the air-conditioning system,

P_{fans} is fan power demand, P_{acc} is the power demand for the cooling system

T_a is the air temperature, m_a is the air mass flow rate, T_w and m_w are the water temperature and mass flow rate respectively. $m_{a(d)}$, $T_{w(d)}$ and $m_{w(d)}$ are design values.

The building description files for the TYPE 56 were made using data from the DOE2 simulation from Chapter 4. The meteorological file used there was also used here. The buildings were simulated with sunscreens on them and the following results were obtained.

5.5 Results of Simulating Suntracking PV Modules

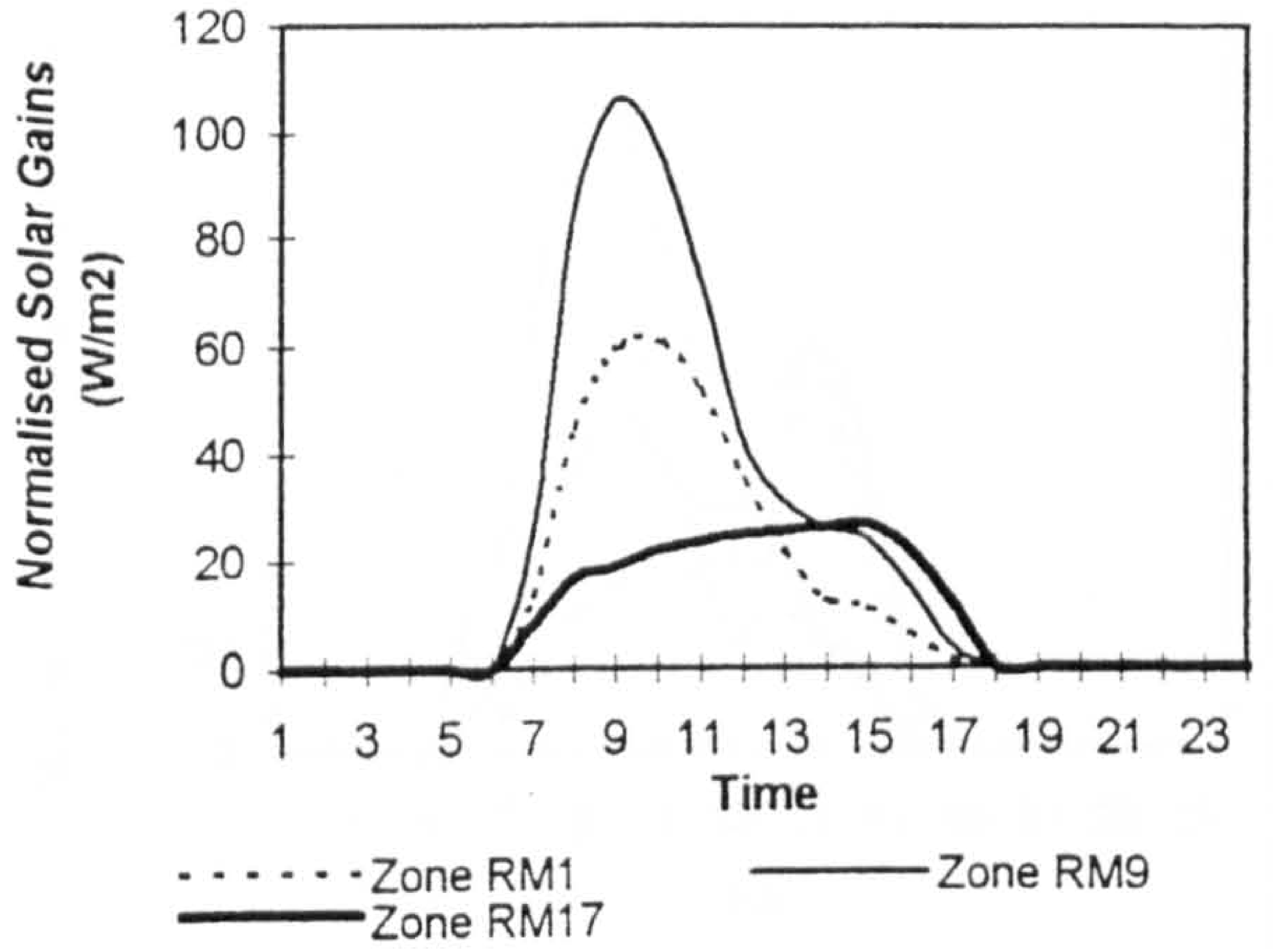


Figure 5.7.1a: Business Hotel: Solar Gains in July with Sunshading

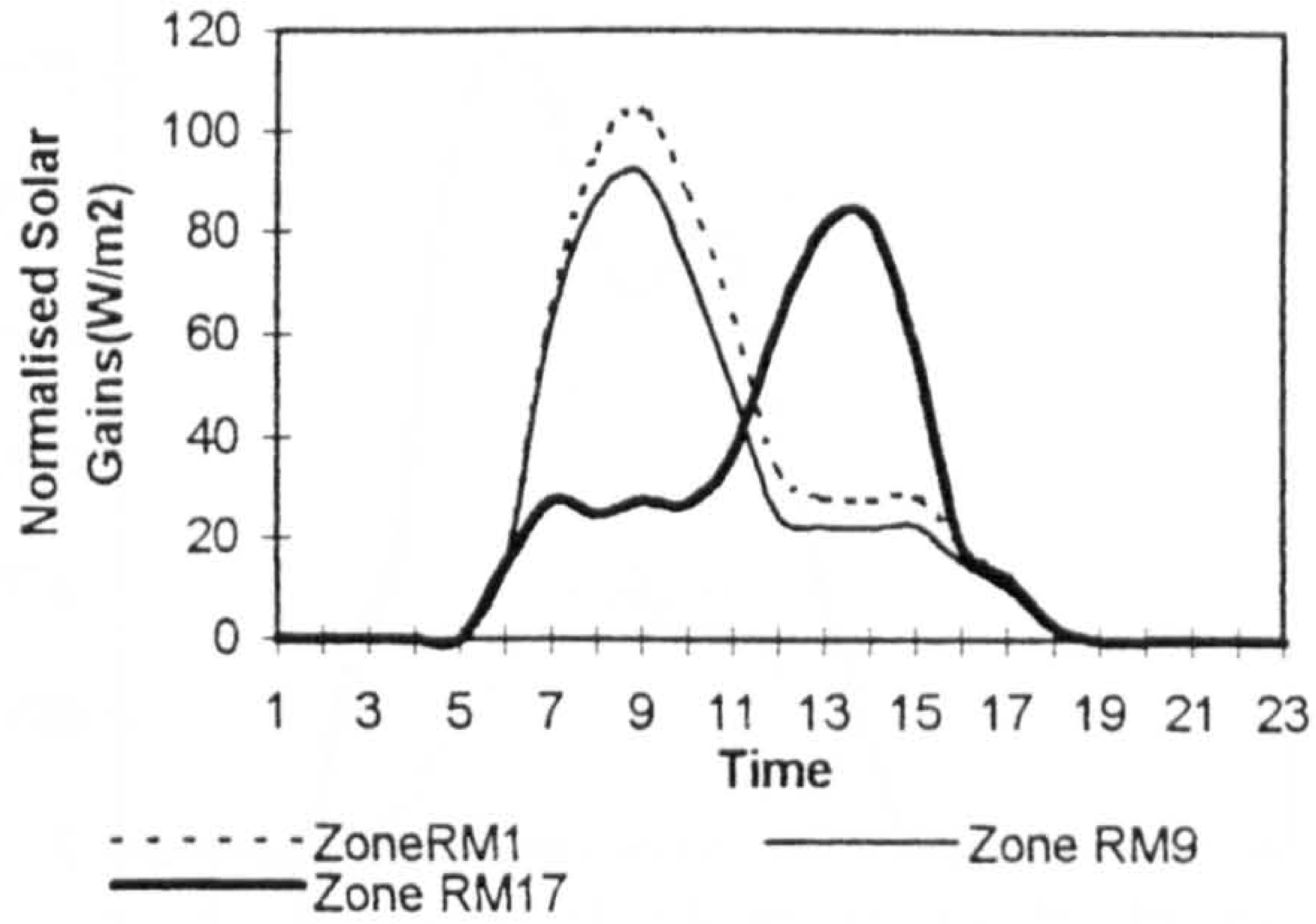


Figure 5.7.1b: Government Building Solar Heat Gains in October with Sunshading

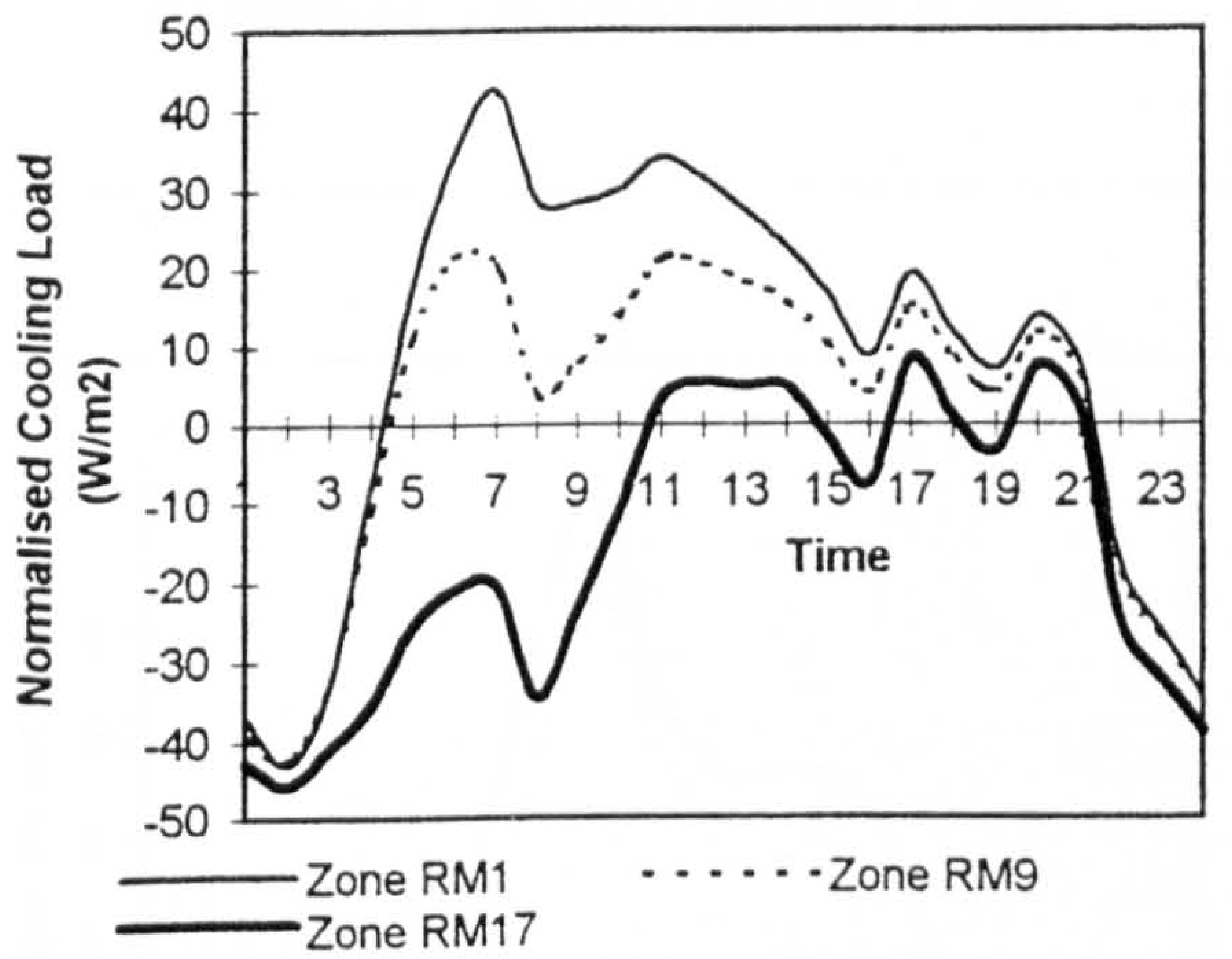


Figure 5.7.1c: Business Hotel: Zone Cooling Loads in July with Sunshading

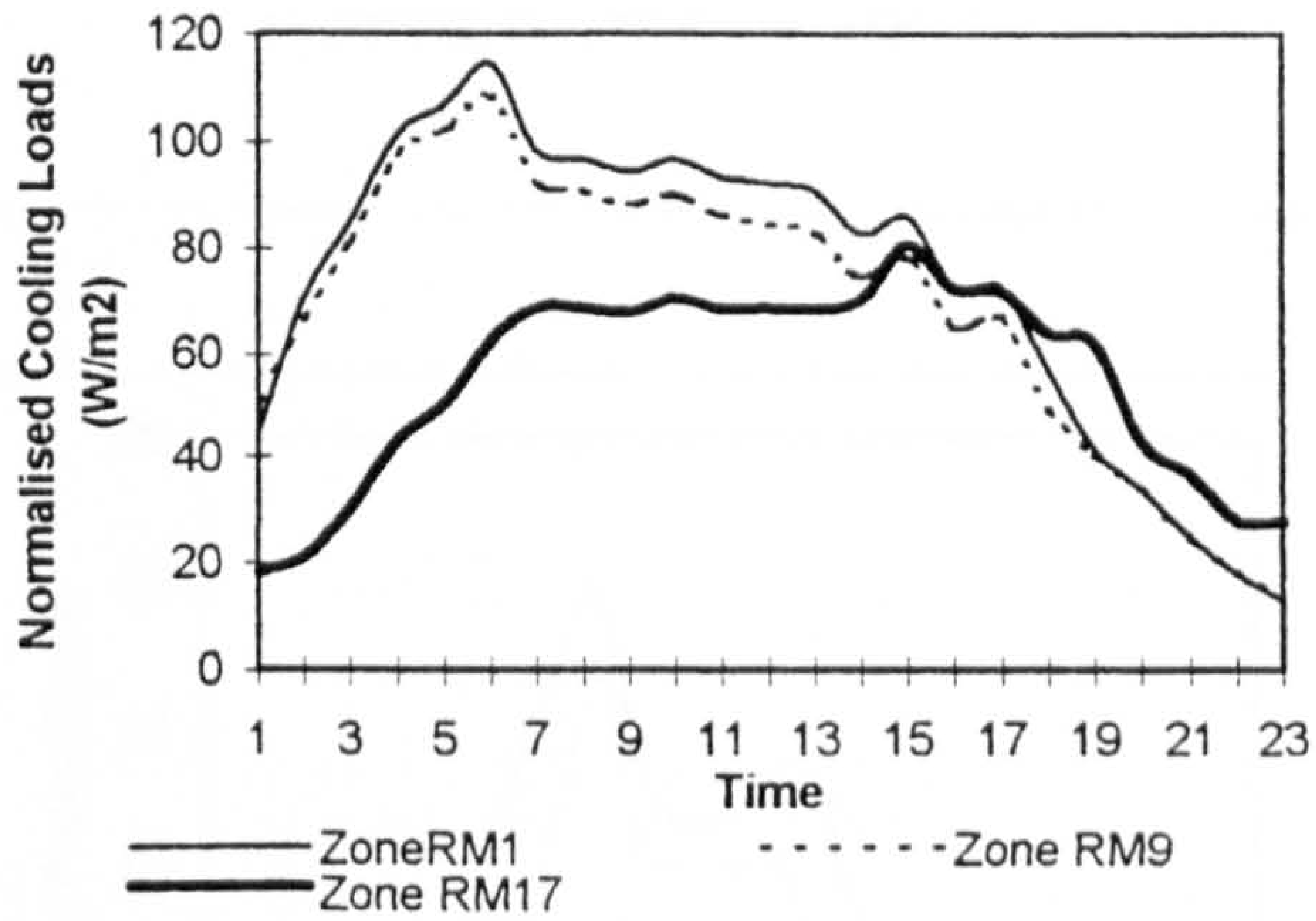


Figure 5.7.1d: Government Building Cooling Loads in October with Sunshading

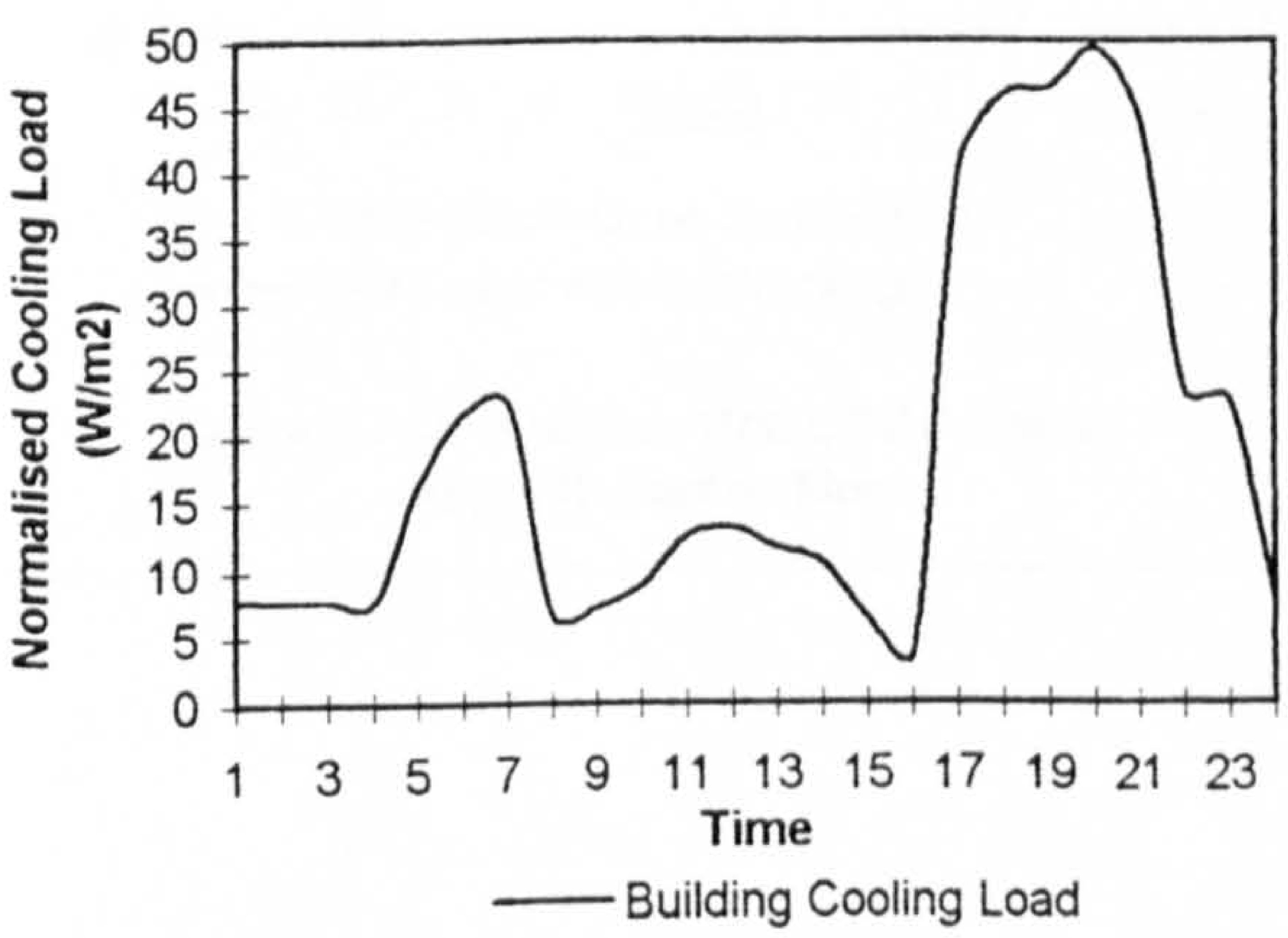


Figure 5.7.1e: Business Hotel: Cooling Load in July with Sunshading

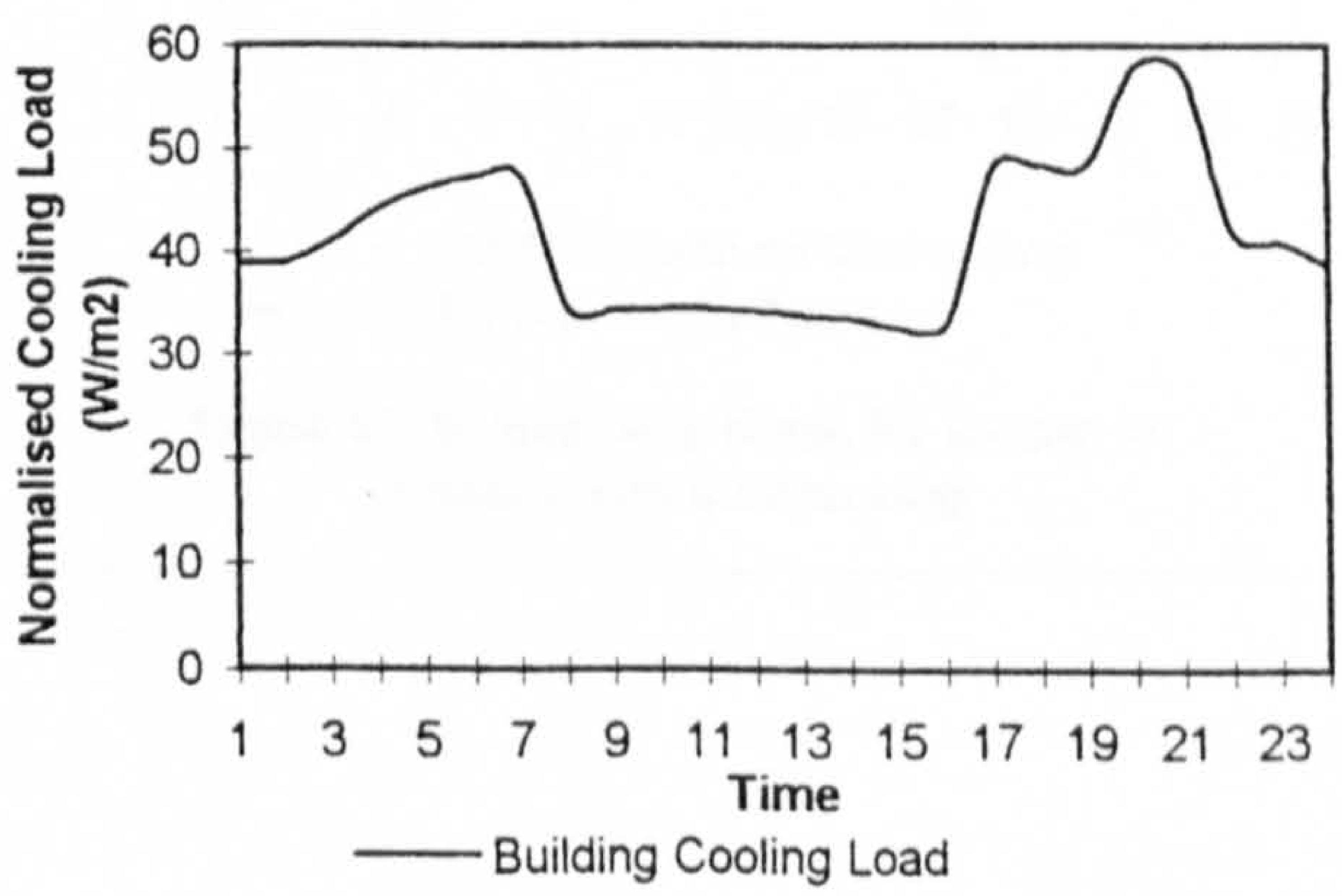


Figure 5.7.1f: Business Hotel: Whole Building Cooling Load in October with Sunshading

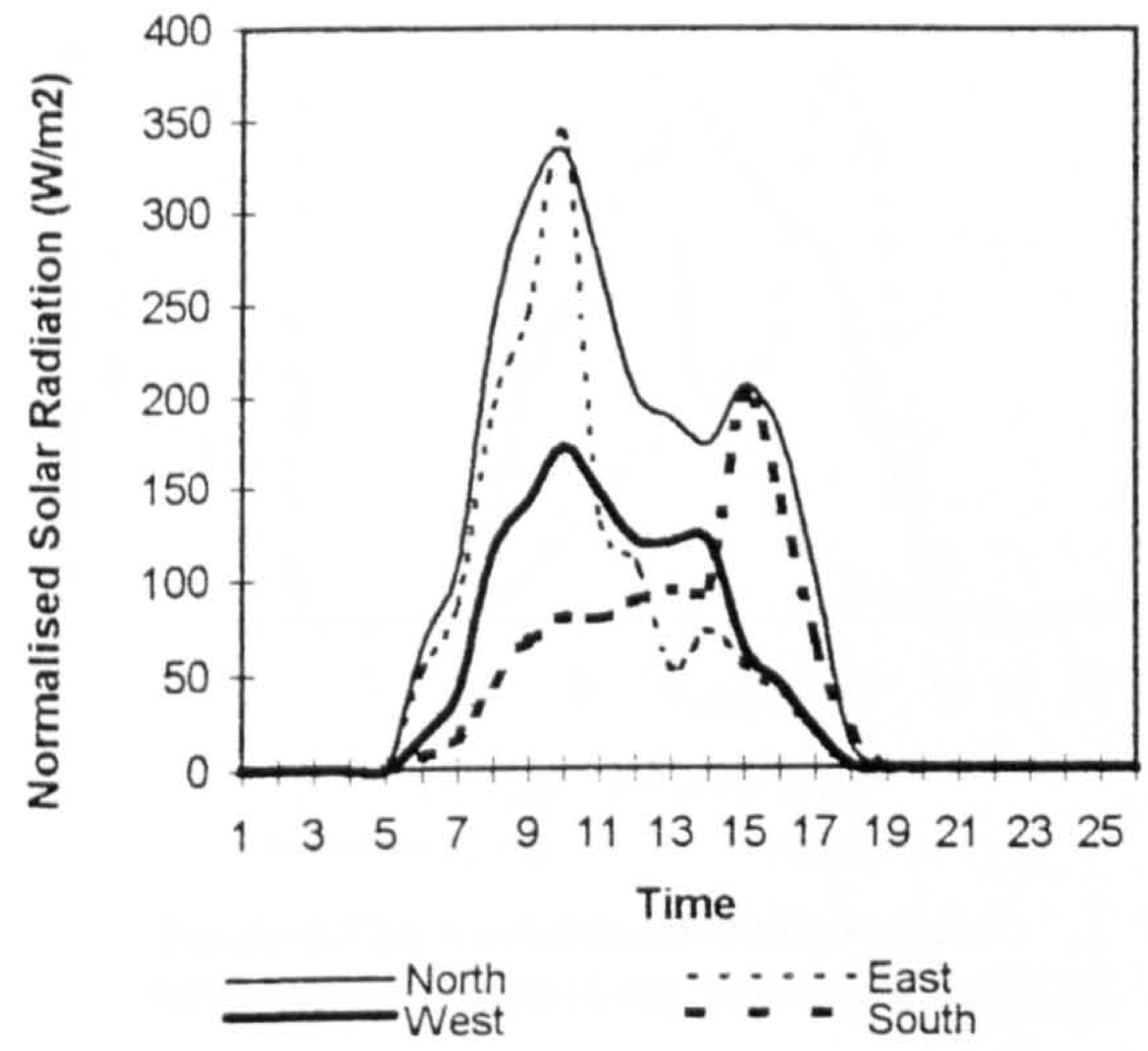


Figure 5.7.1g: Business Hotel: Solar Radiation on Suntracking Modules in July

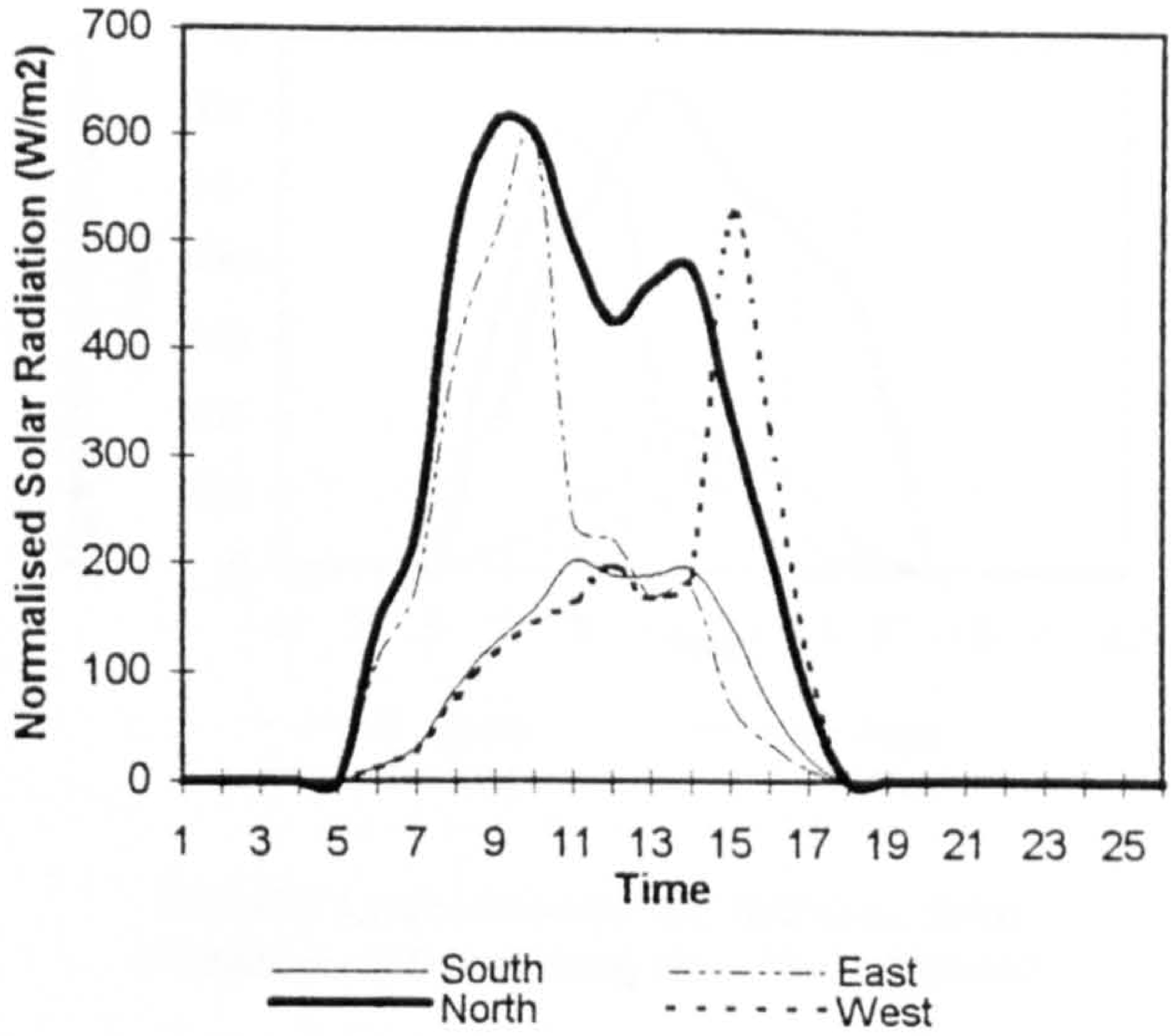


Figure 5.7.1h: Business Hotel: Solar Radiation on Suntracking Modules in October

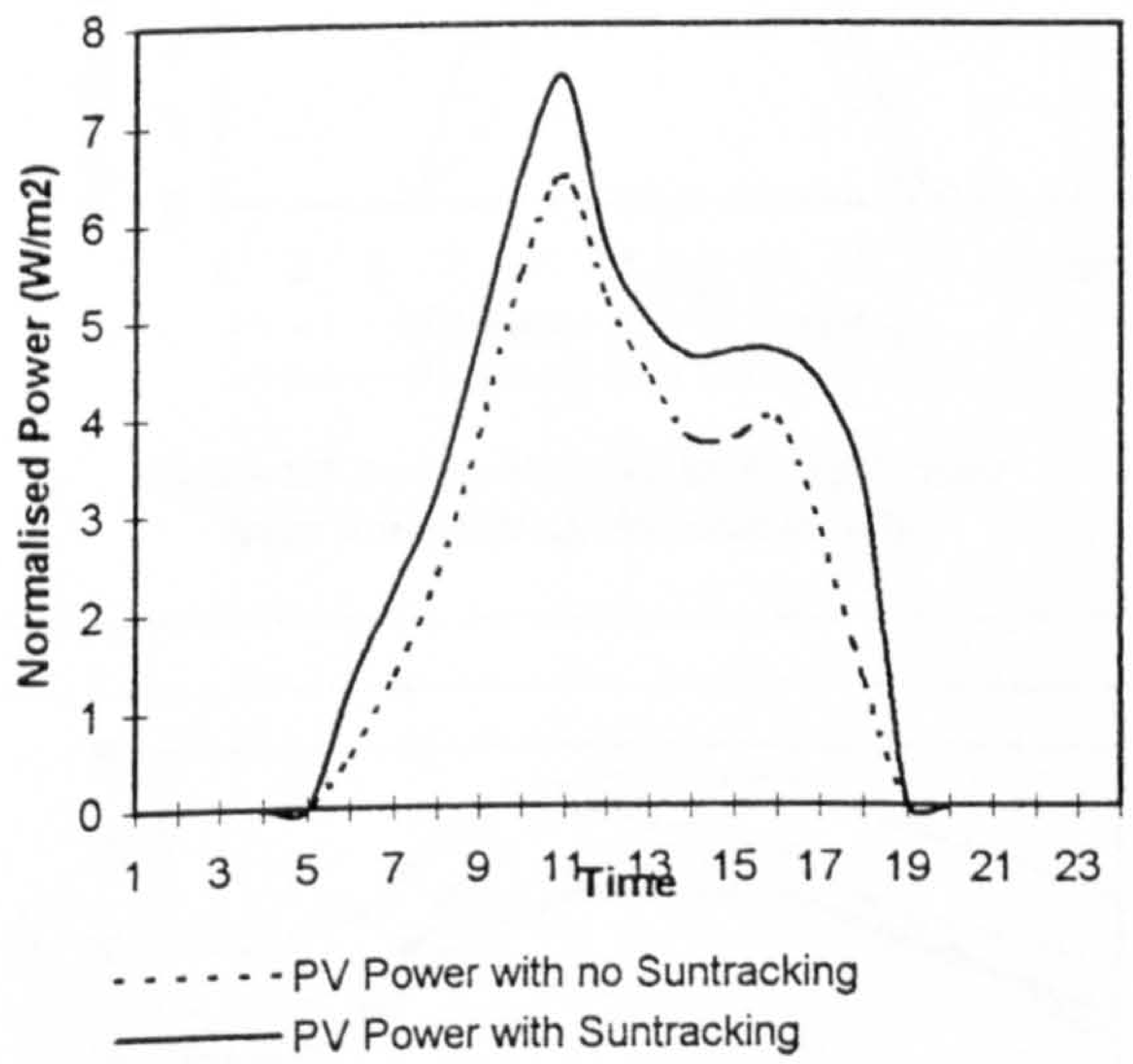


Figure 5.7.1i: Business Hotel, PV Power in July with Suntracking

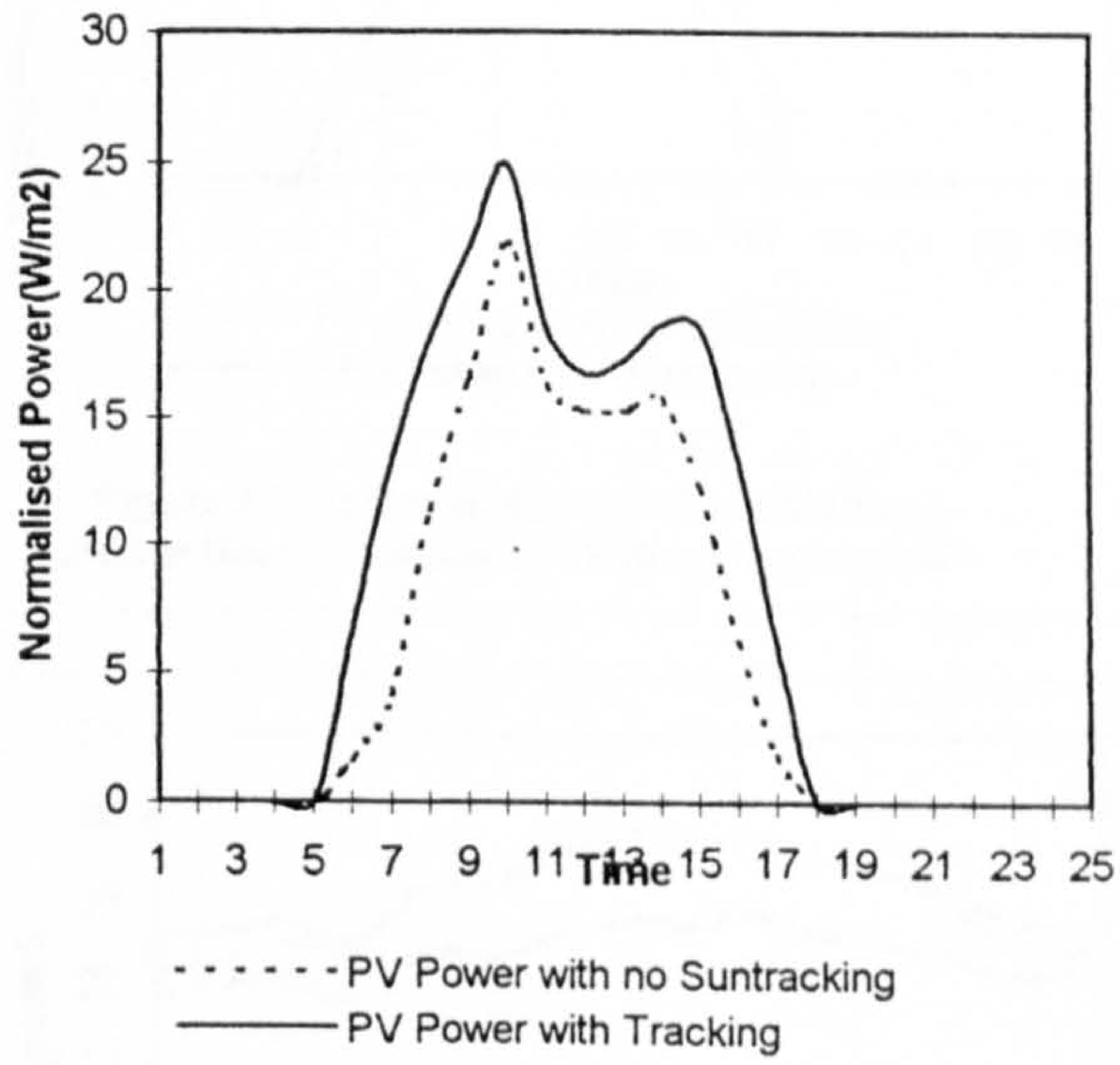


Figure 5.7.1j: Business Hotel, PV Output in October with Suntracking

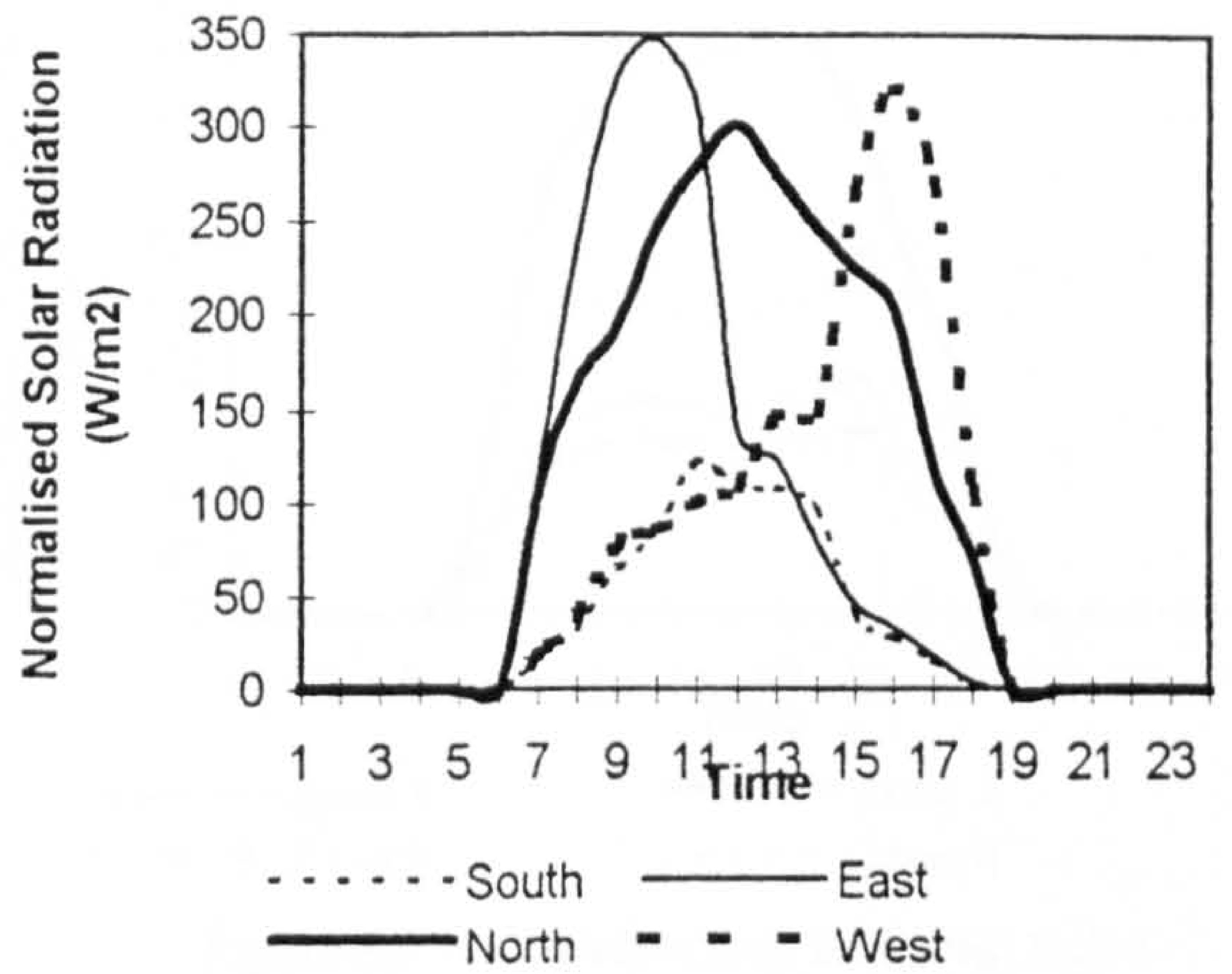


Figure 5.7.2f: Government Building Solar Radiation on Suntracking Modules in July

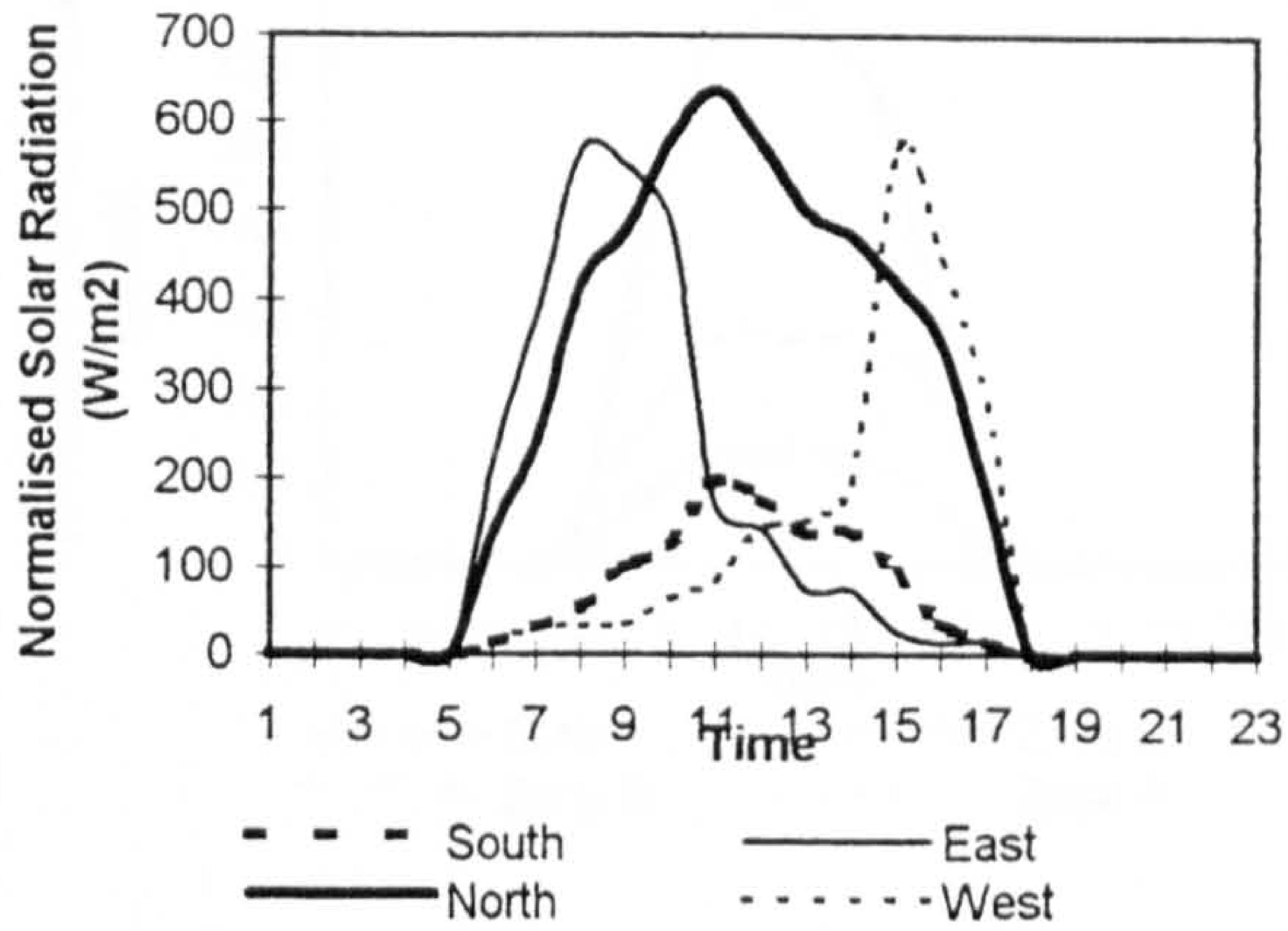


FIGURE 5.7.2h: Government Building: Solar Radiation on Suntracking Modules in October

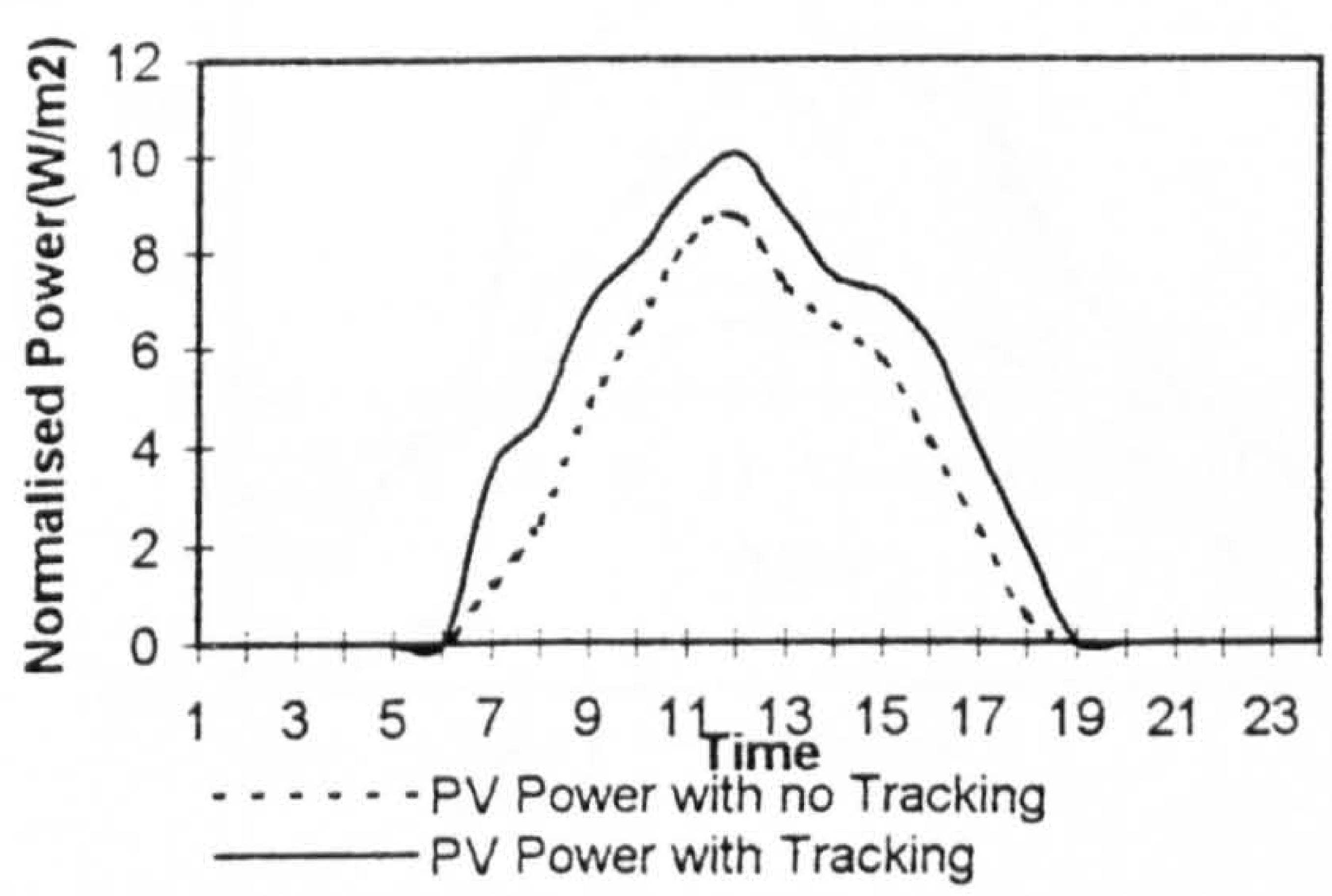


Figure 5.7.2i: Government Building: Power from Suntracking Modules in July

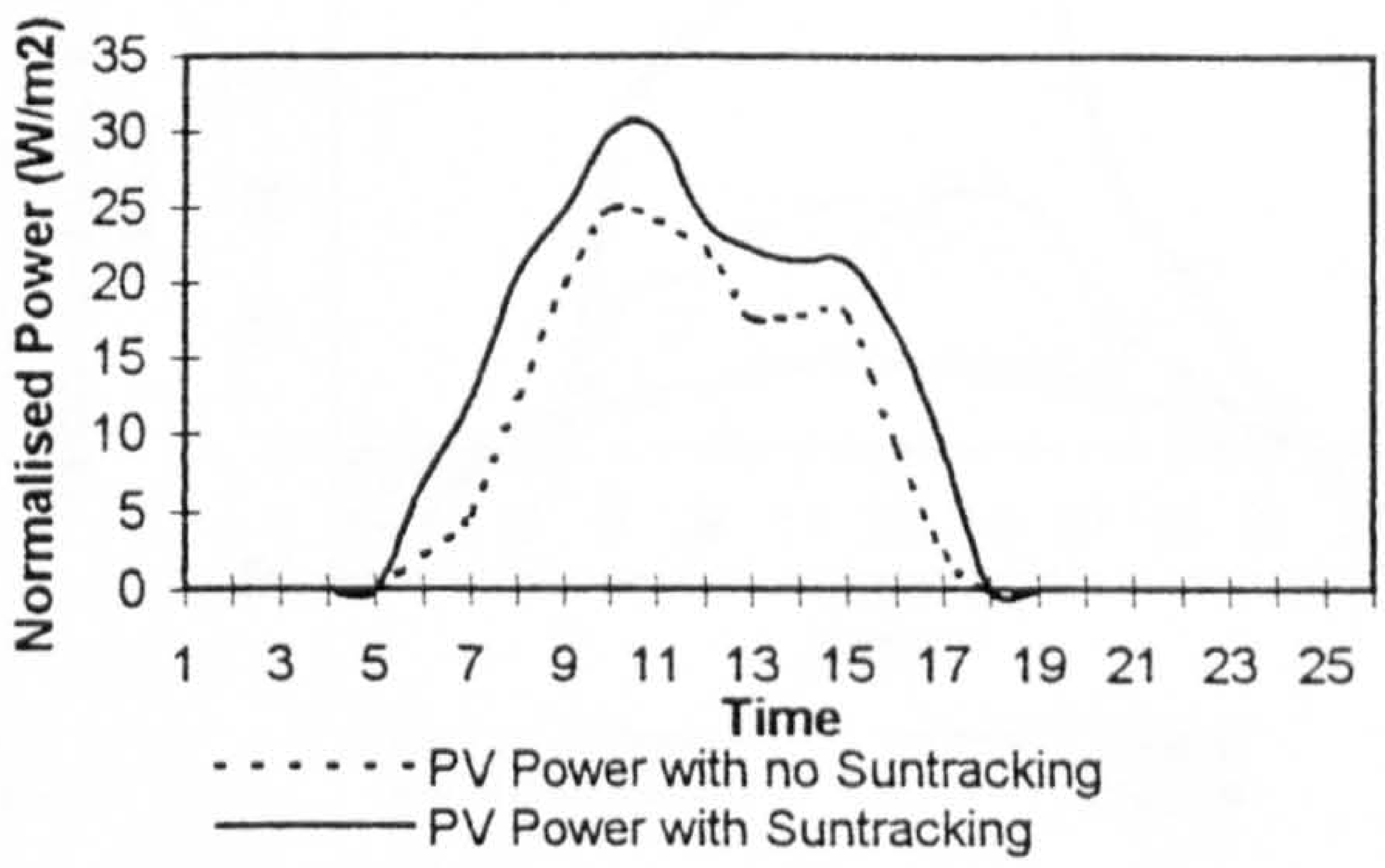


Figure 5.7.2j: Government Office Building, Power from Suntracking Modules in October

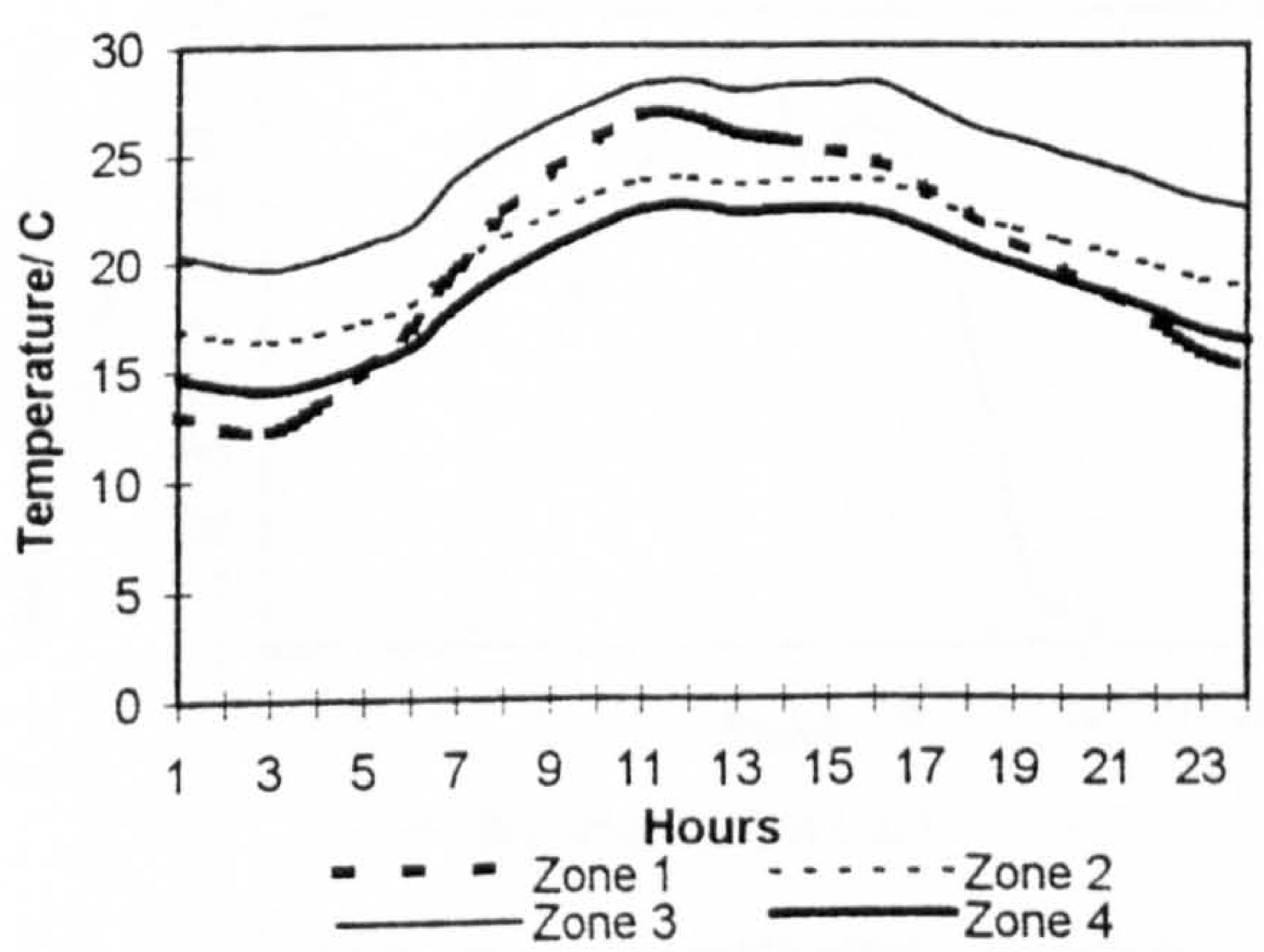


Figure 5.7.2k: Government Building: Zone Temperatures with Sunshading in July

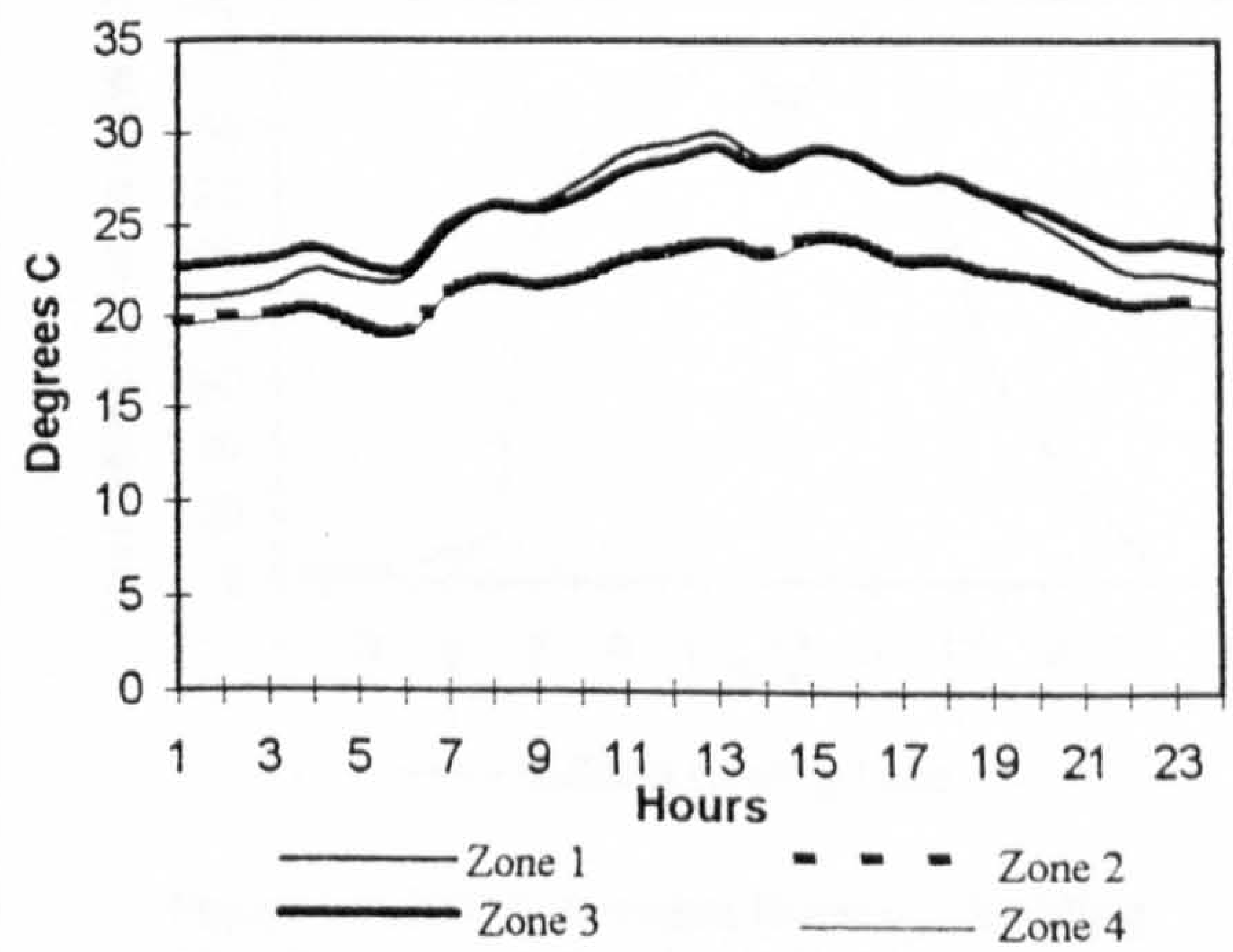


Figure 5.7.2l: Government Building Zone Temperatures with Tracking in October

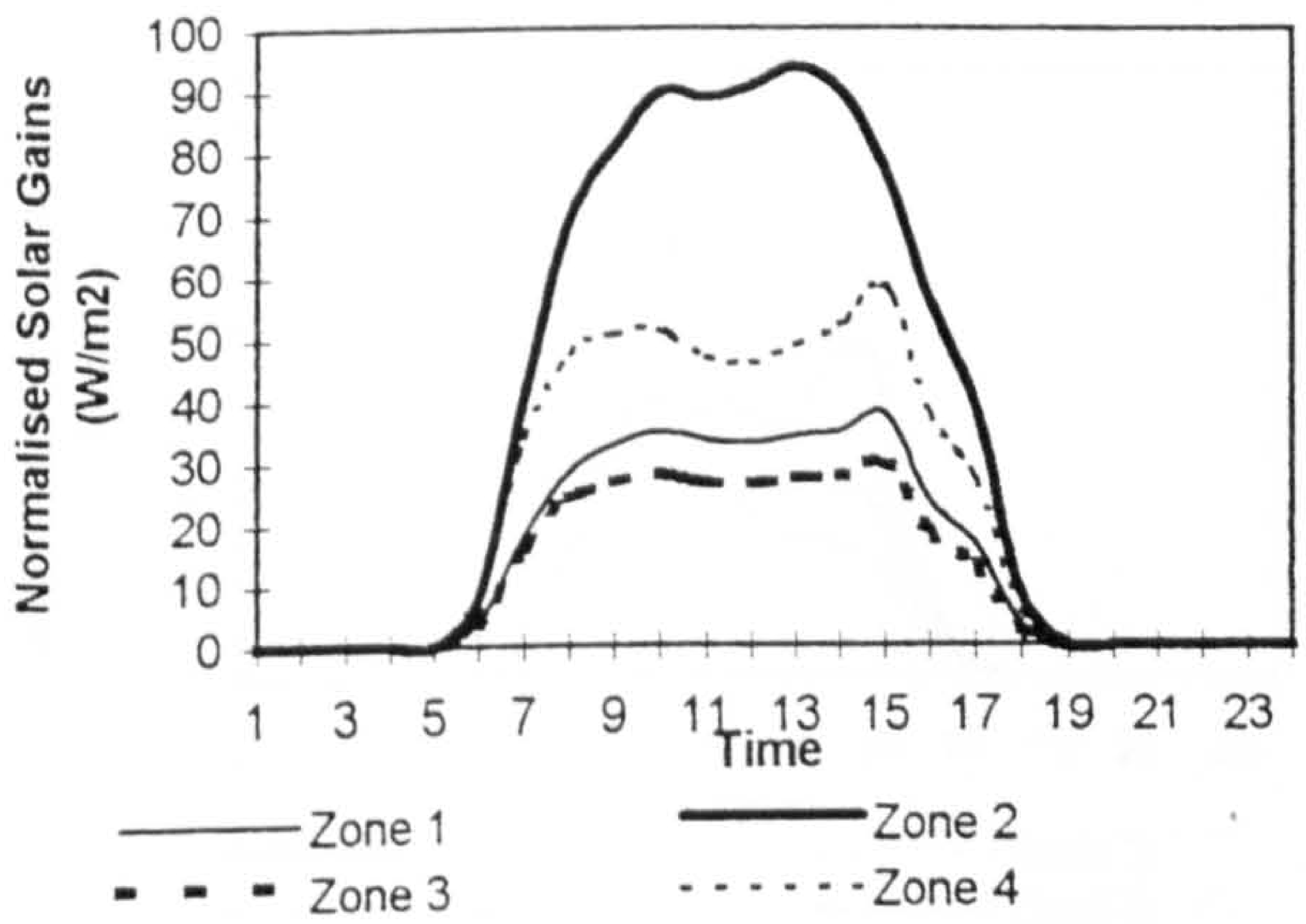


Figure 5.7.2a: Government Building: Solar Gains in July with Sunshading

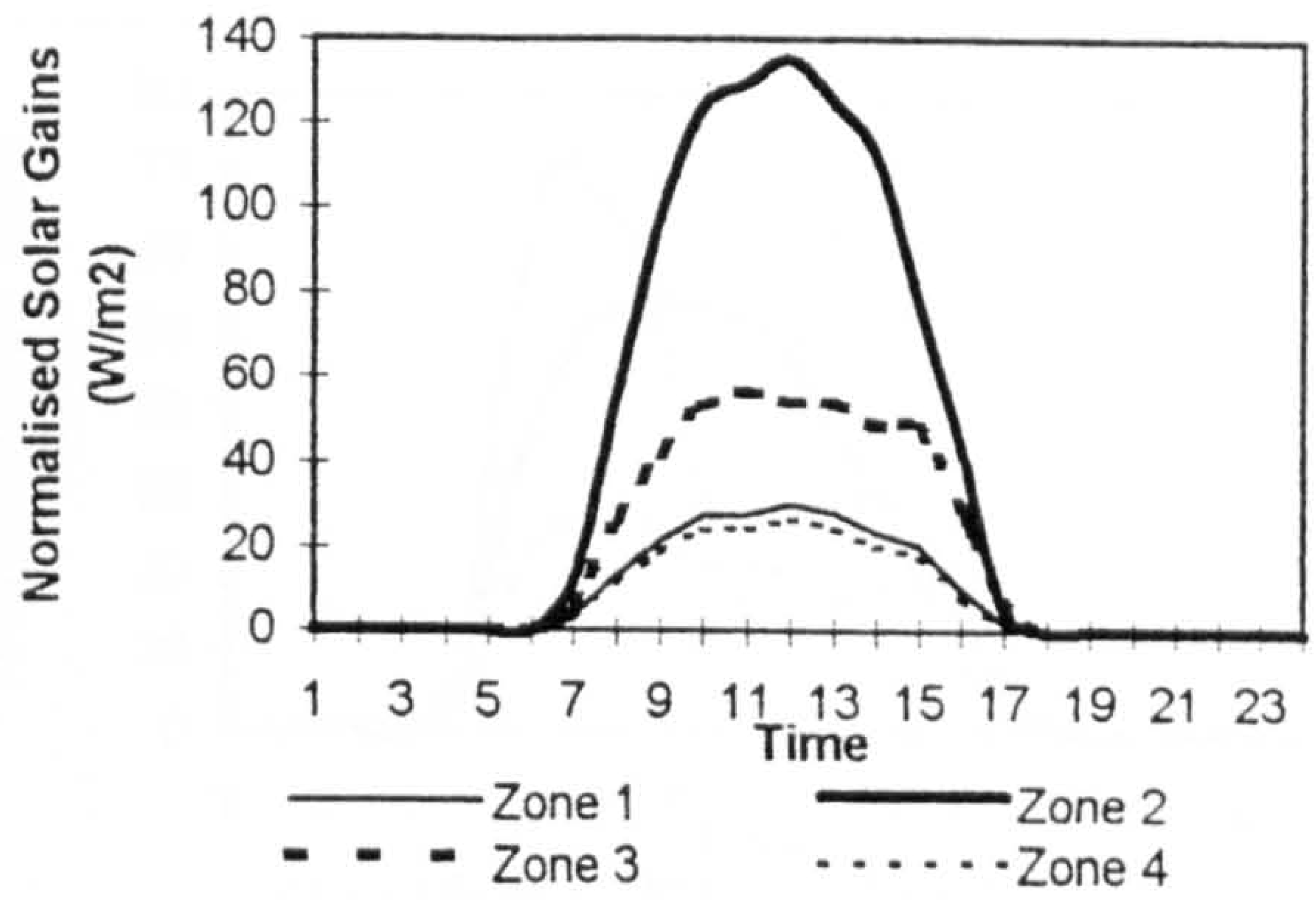


Figure 5.7.2b: Government Building: Solar Gains in October with Sunshading

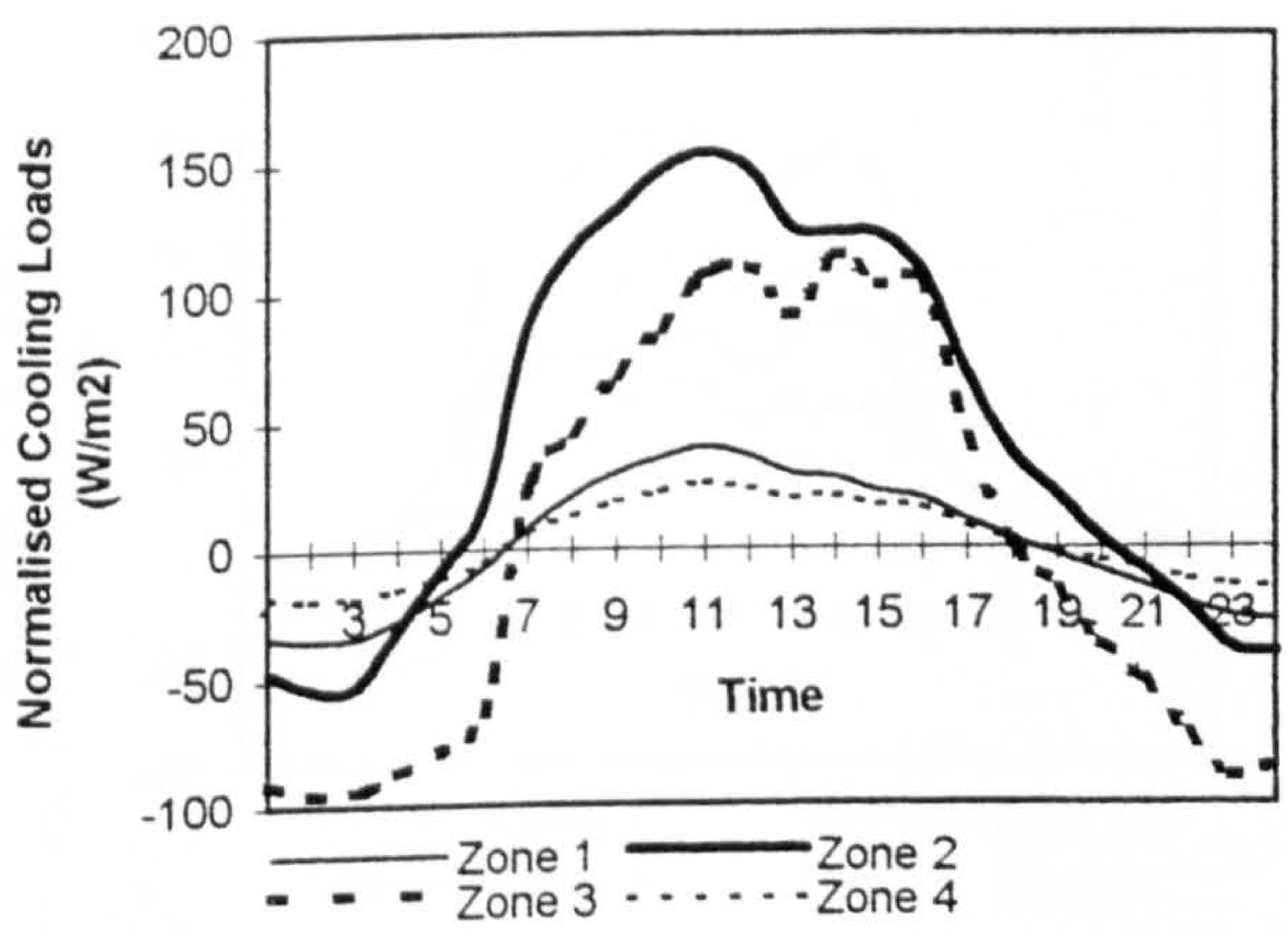


Figure 5.7.2c: Government Building: Zone Cooling Loads in July with Sunshading

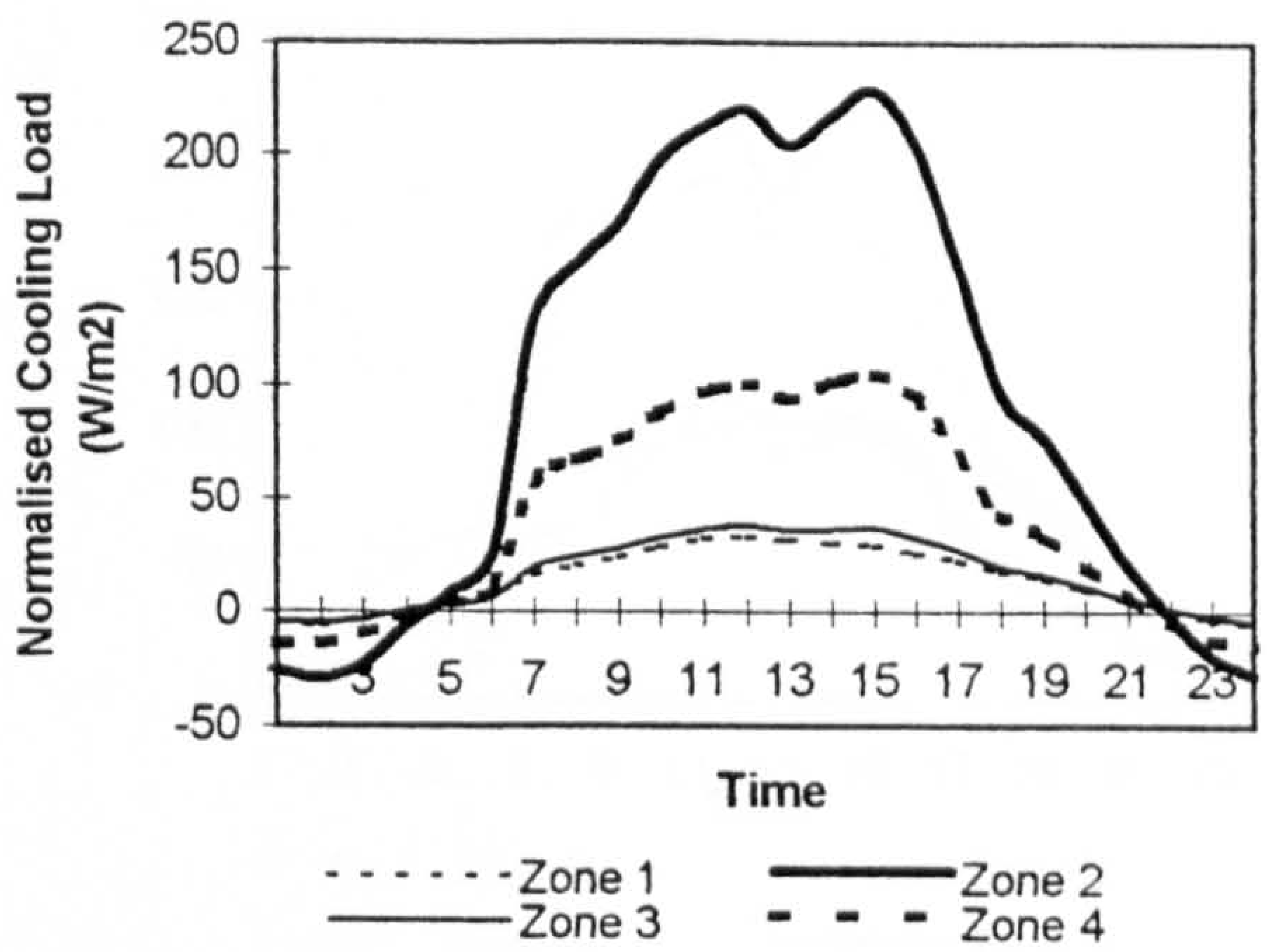


Figure 5.7.2d: Government Building: Zone Cooling Loads in October with Sunshading

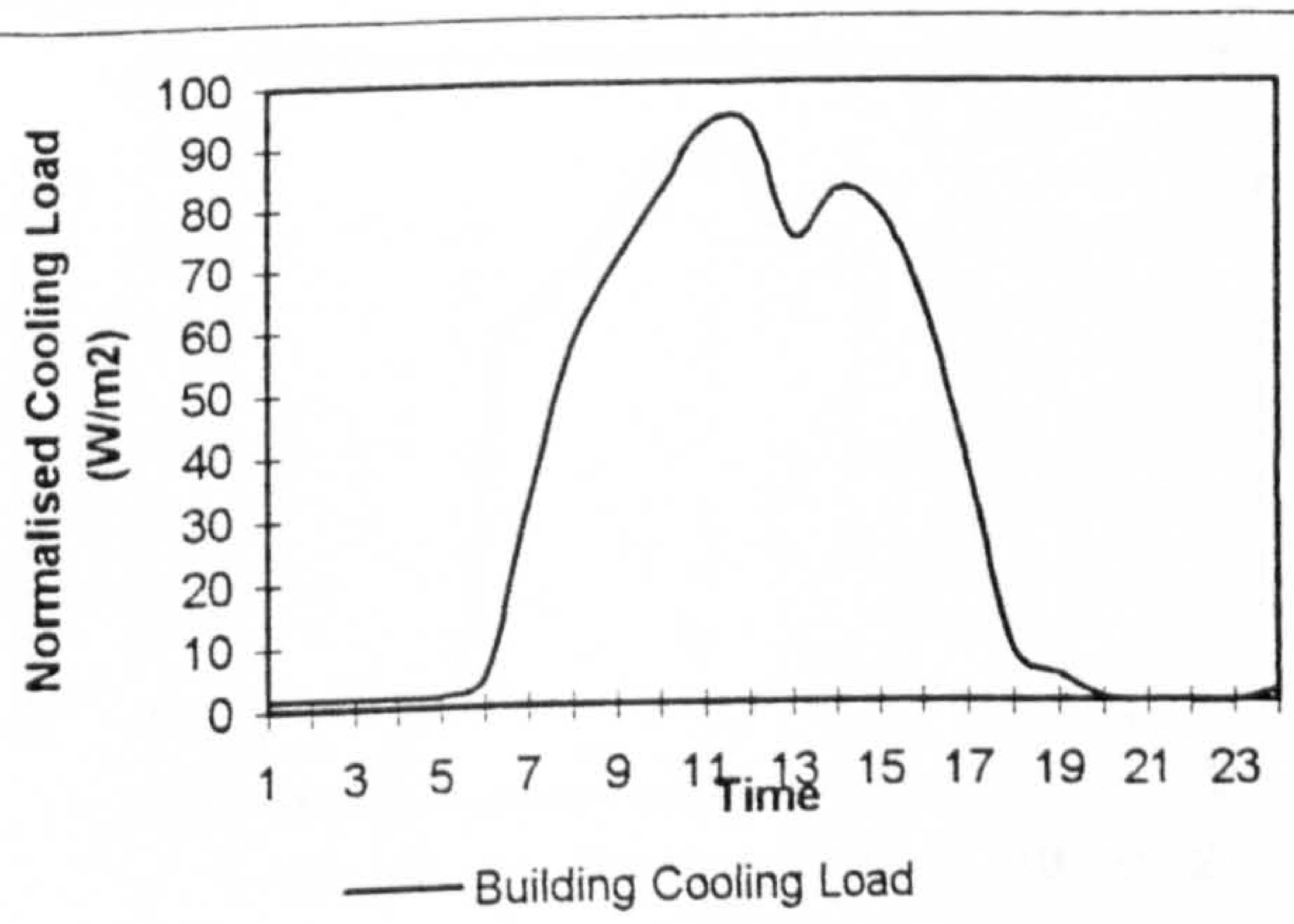


Figure 5.7.2e: Government Building: Building Cooling Load in July with Sunshading

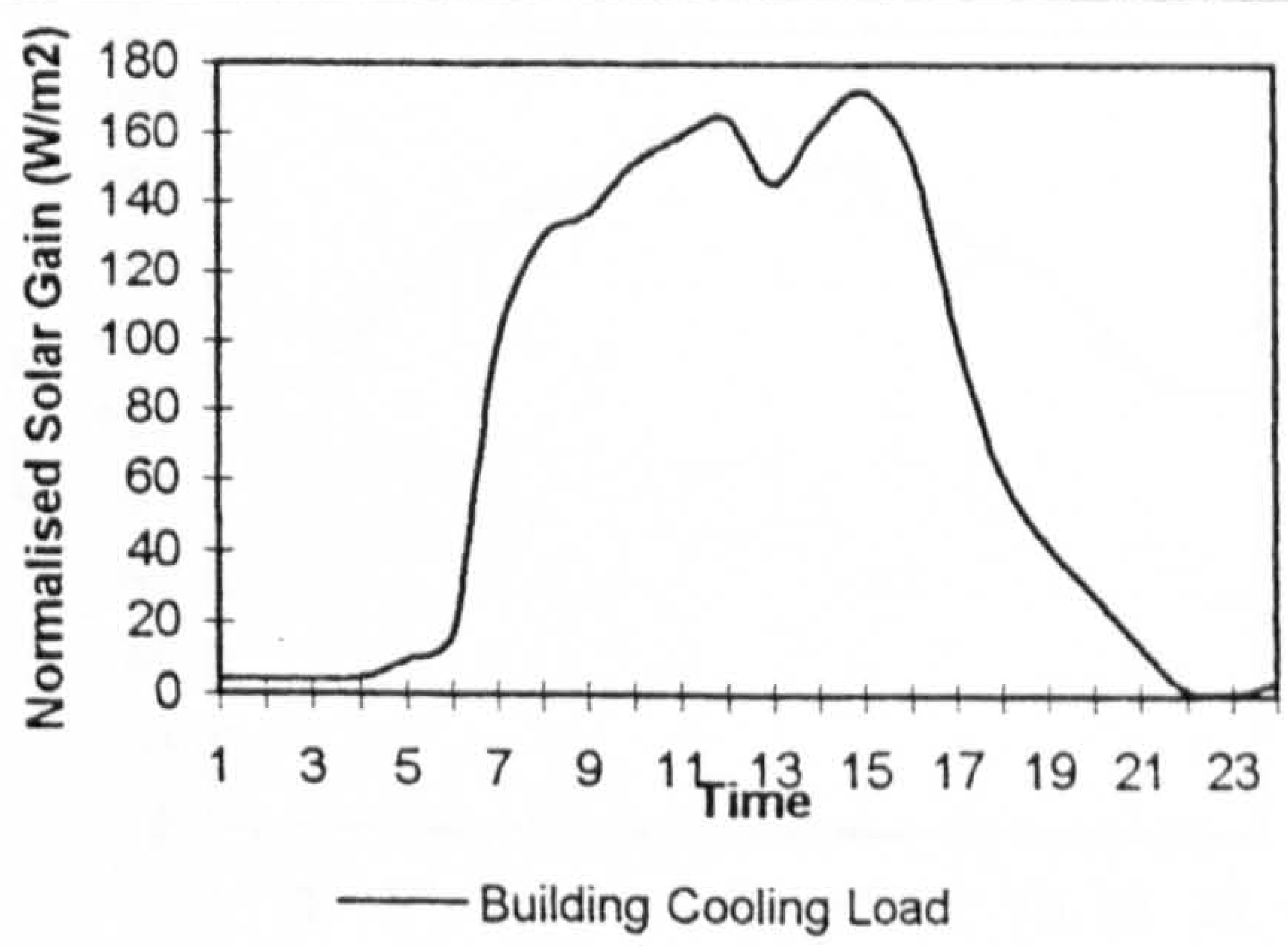


Figure 5.7.2f: Government Building: Building Cooling Load in October with Sunshading

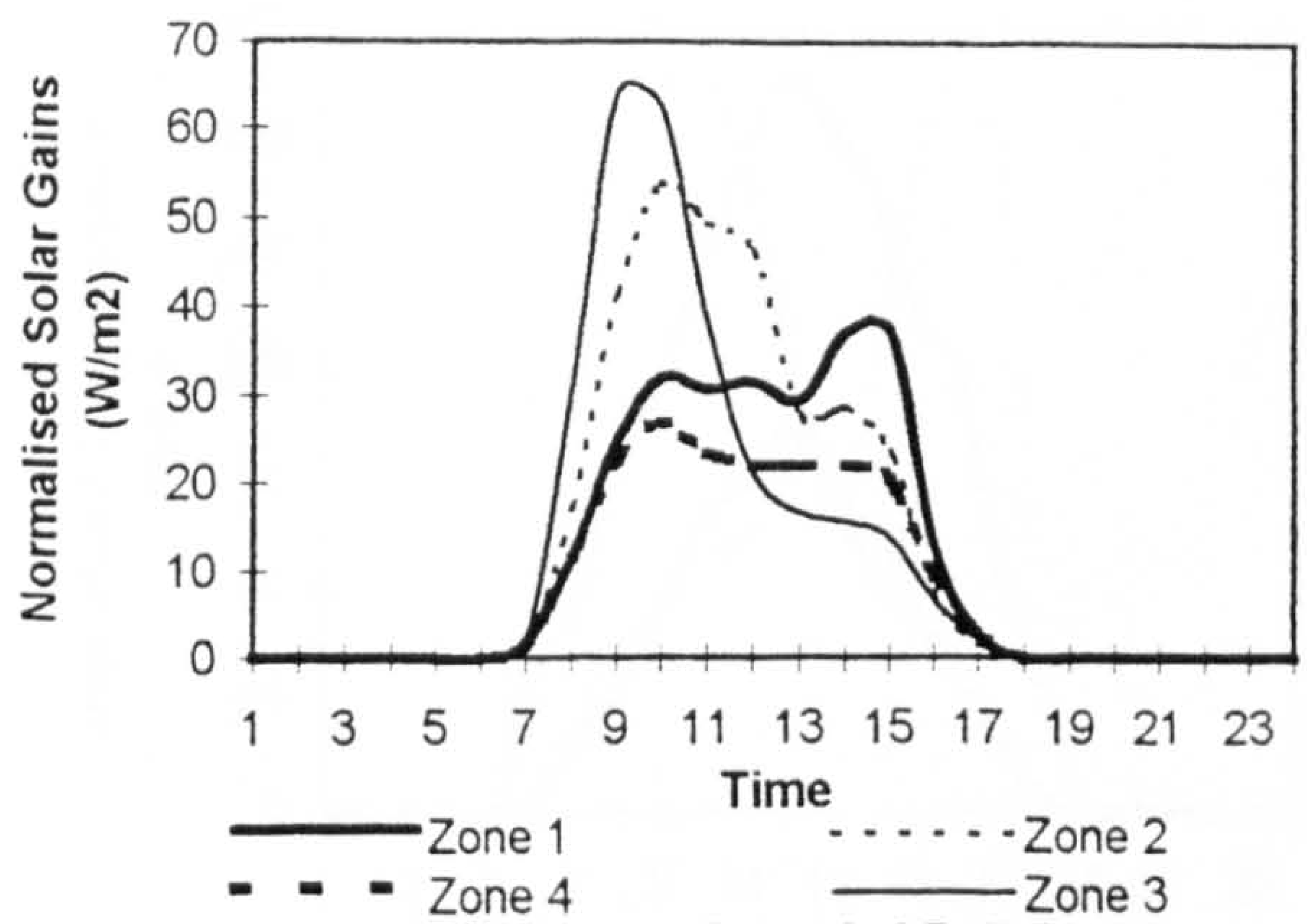


Figure 5.7.3a: Tenant Occupied Building: Solar gains in July with Sunshading

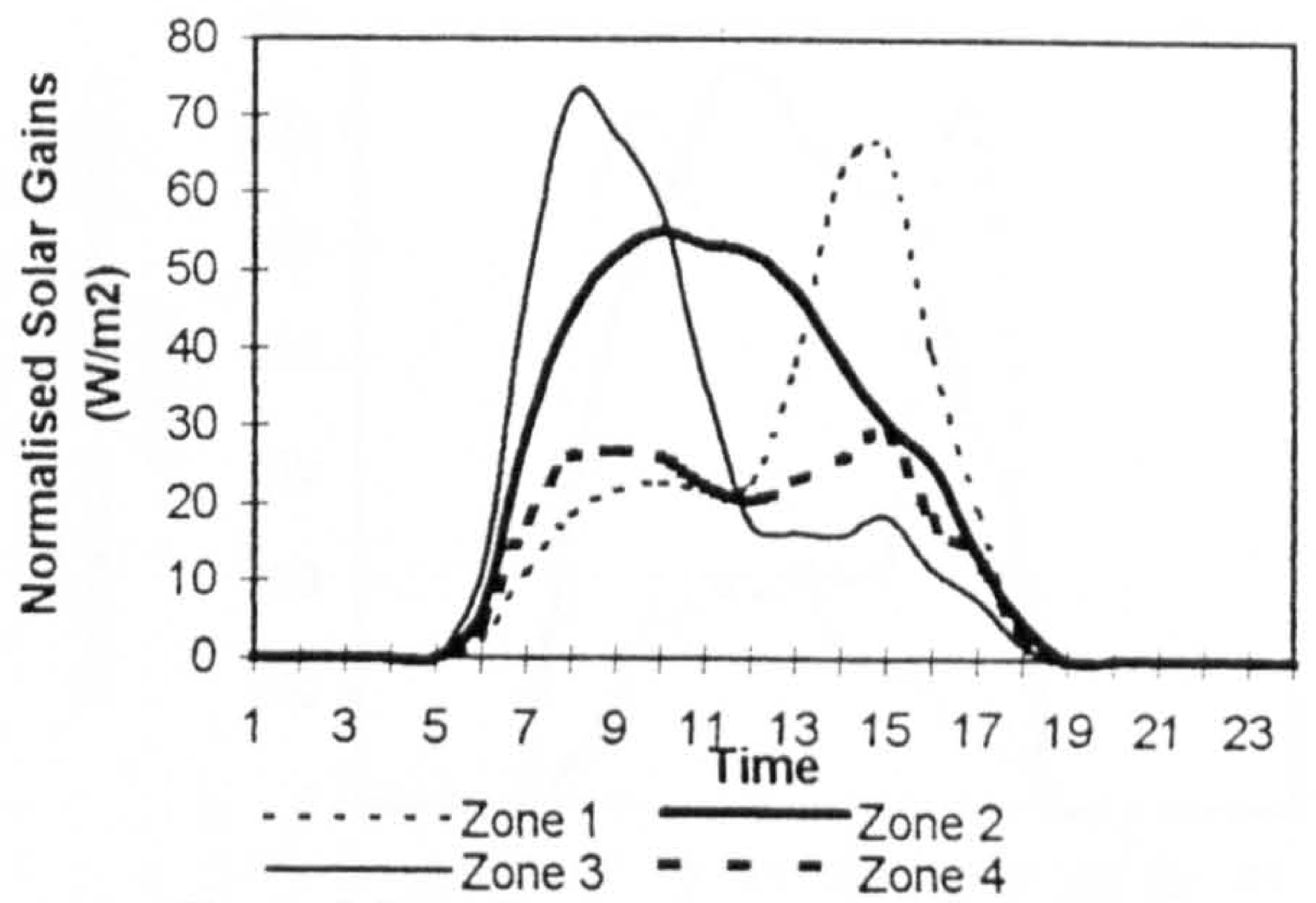


Figure 5.7.3b: Tenant Occupied Building: Solar Gains in October with Sunshading

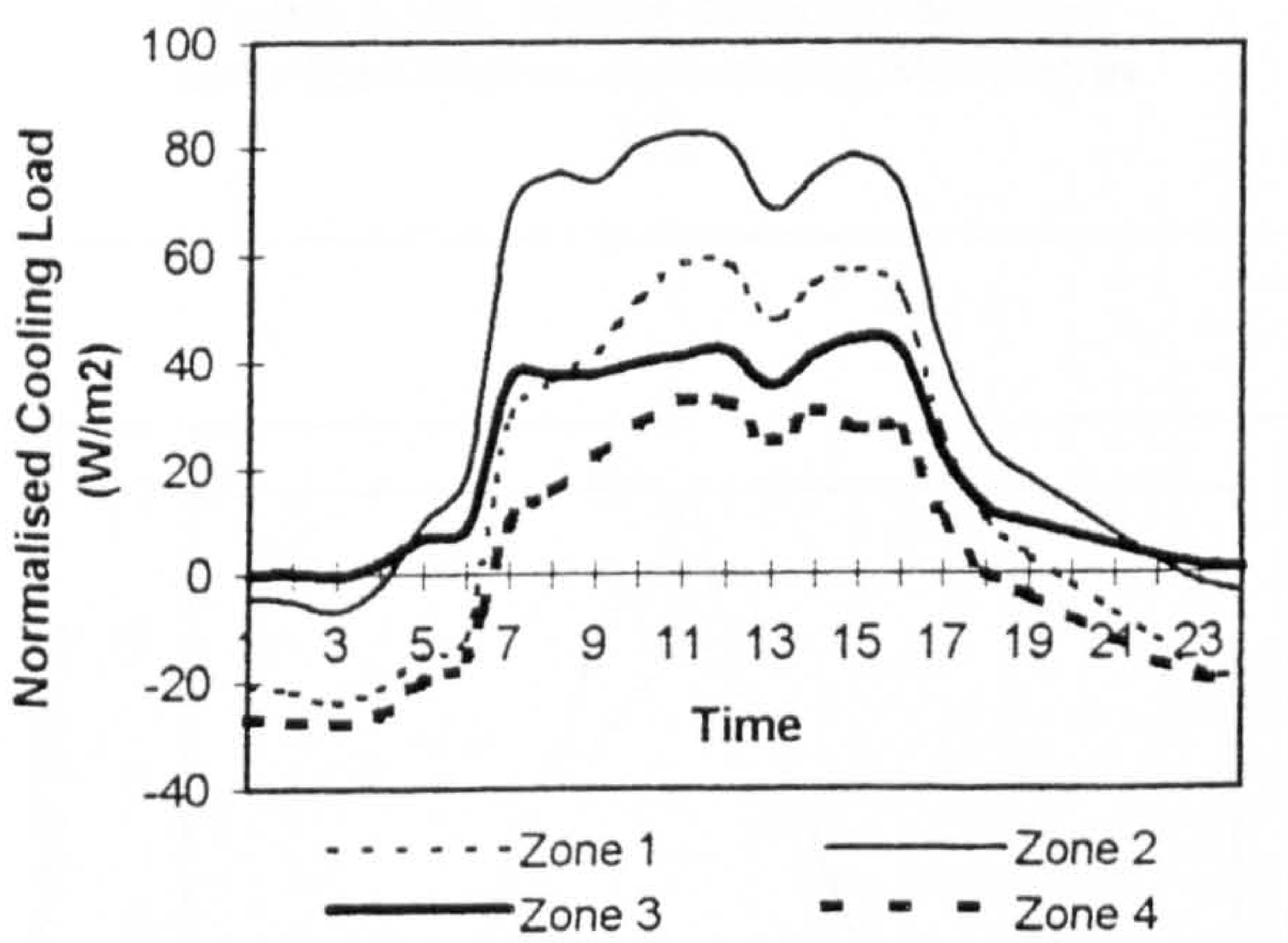


Figure 5.7.3c: Tenant Occupied Building: Zone Cooling Loads in July with Sunshading

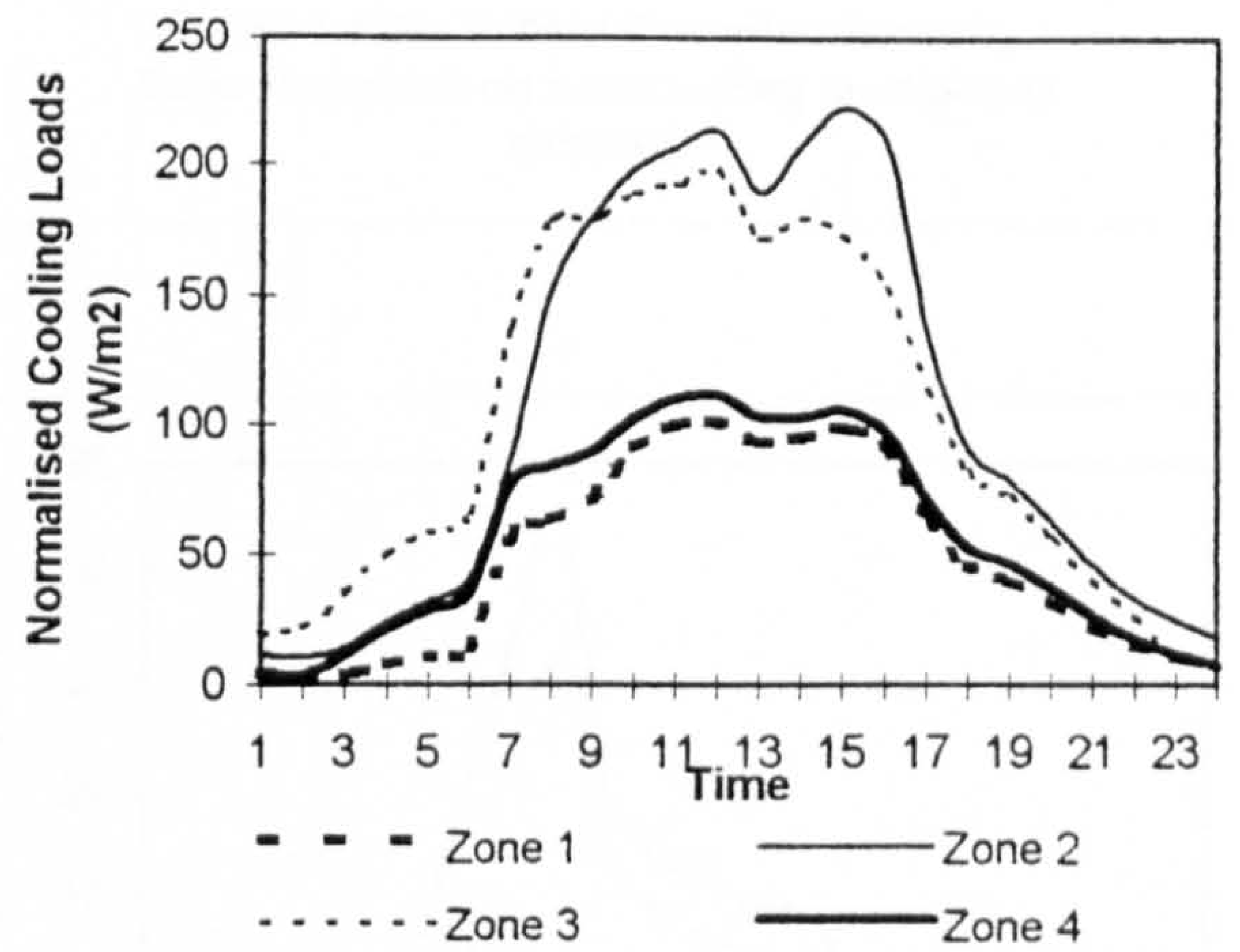


Figure 5.7.3d: Tenant Occupied Building: Zone Coolin Loads with Sunshading

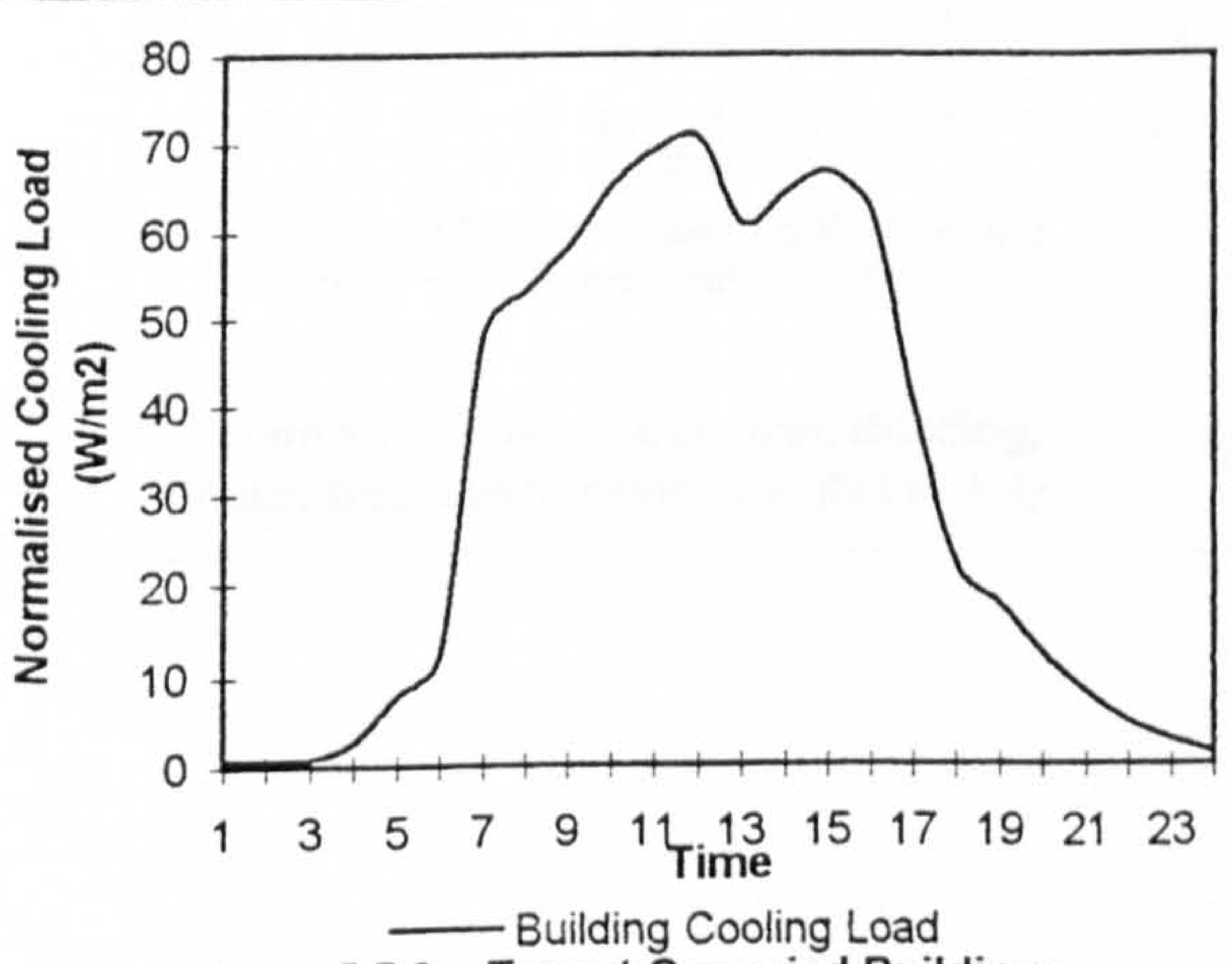


Figure 5.7.3e: Tenant Occupied Building: Building Cooling Load in July with Sunshading

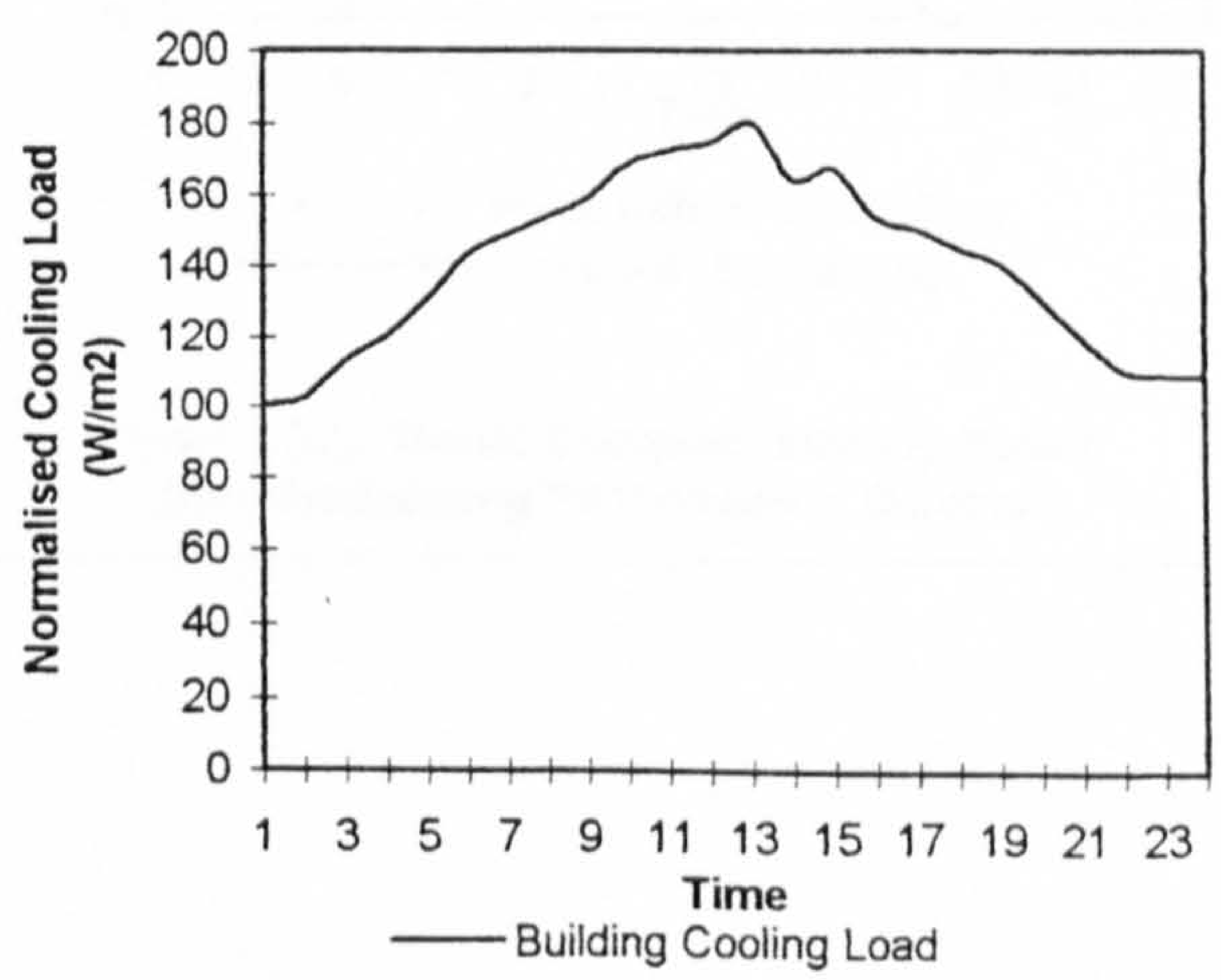


Figure 5.7.2f: Tenant Occupied Building: Building Cooling Load in October with Sunshading

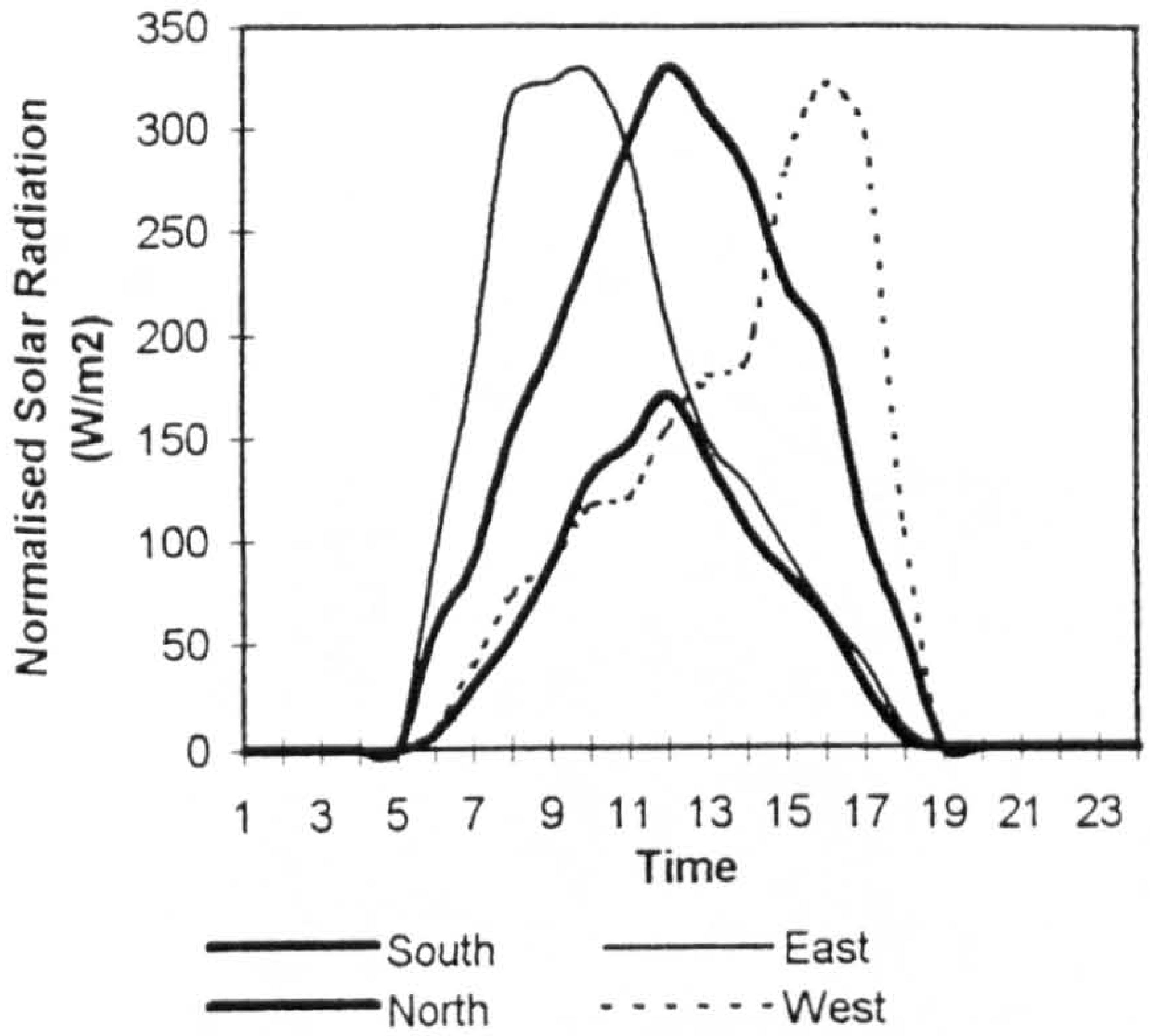


Figure 5.7.3g: Tenant Occupied Building: Solar Radiation on Suntracking Modules in July

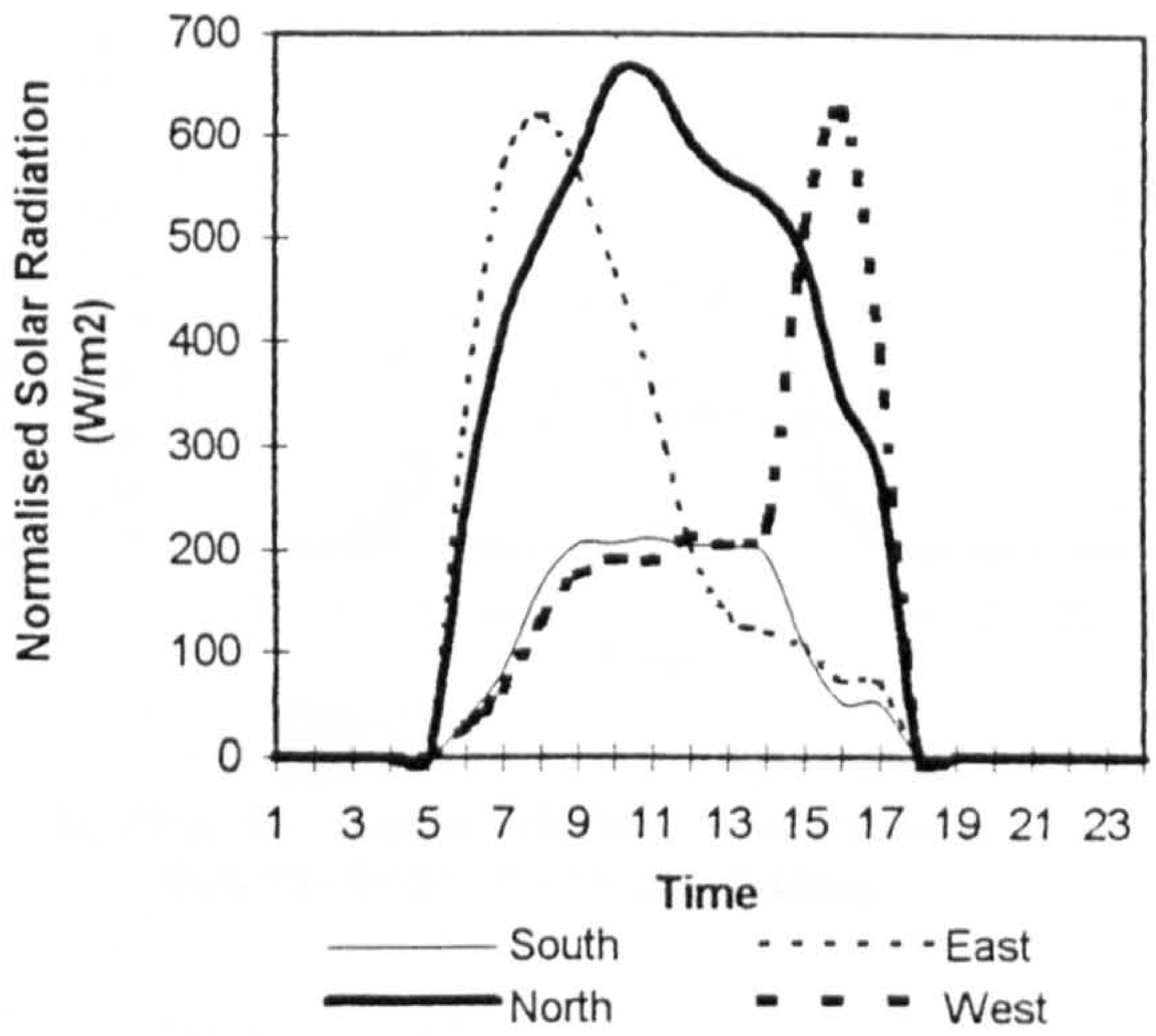


Figure 5.7.3h: Tenant Occupied Building: Solar Radiation on Suntracking Modules in October

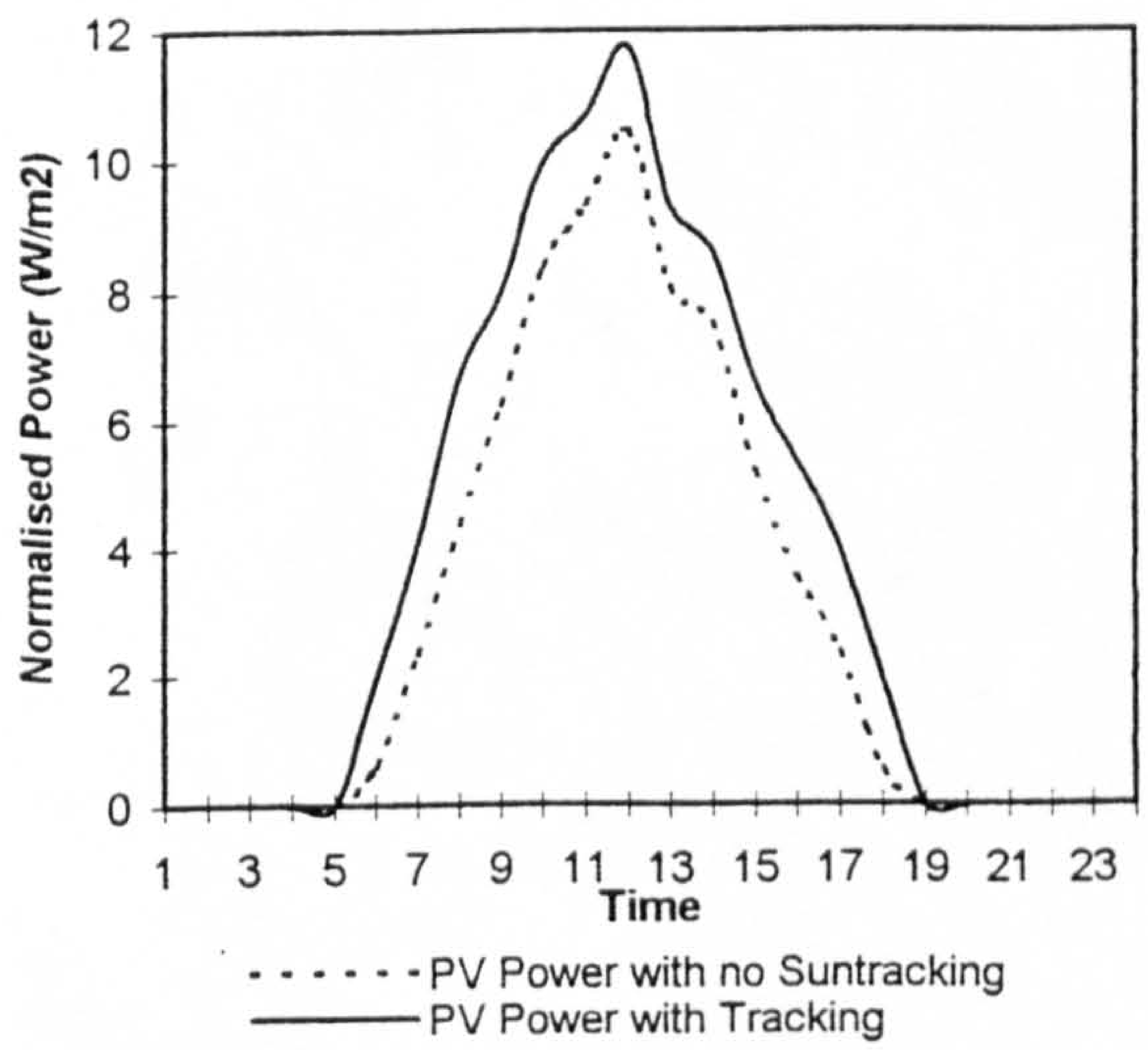


Figure 5.7.3i: Tenant Occupied Building, Power from Suntracking Modules in July

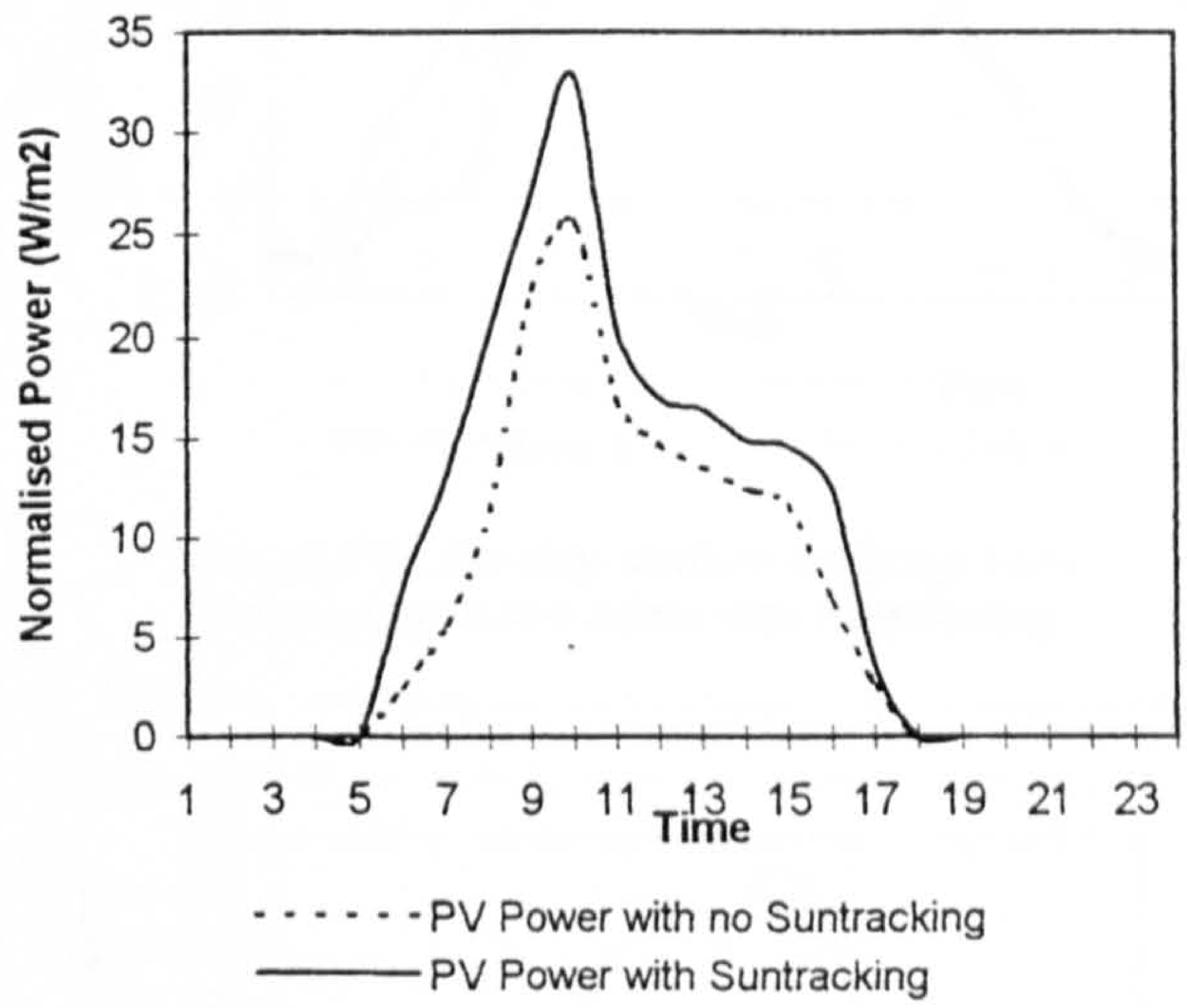


Figure 5.7.2j: Tenant Occupied Building: Power from Suntracking PV Modules in October

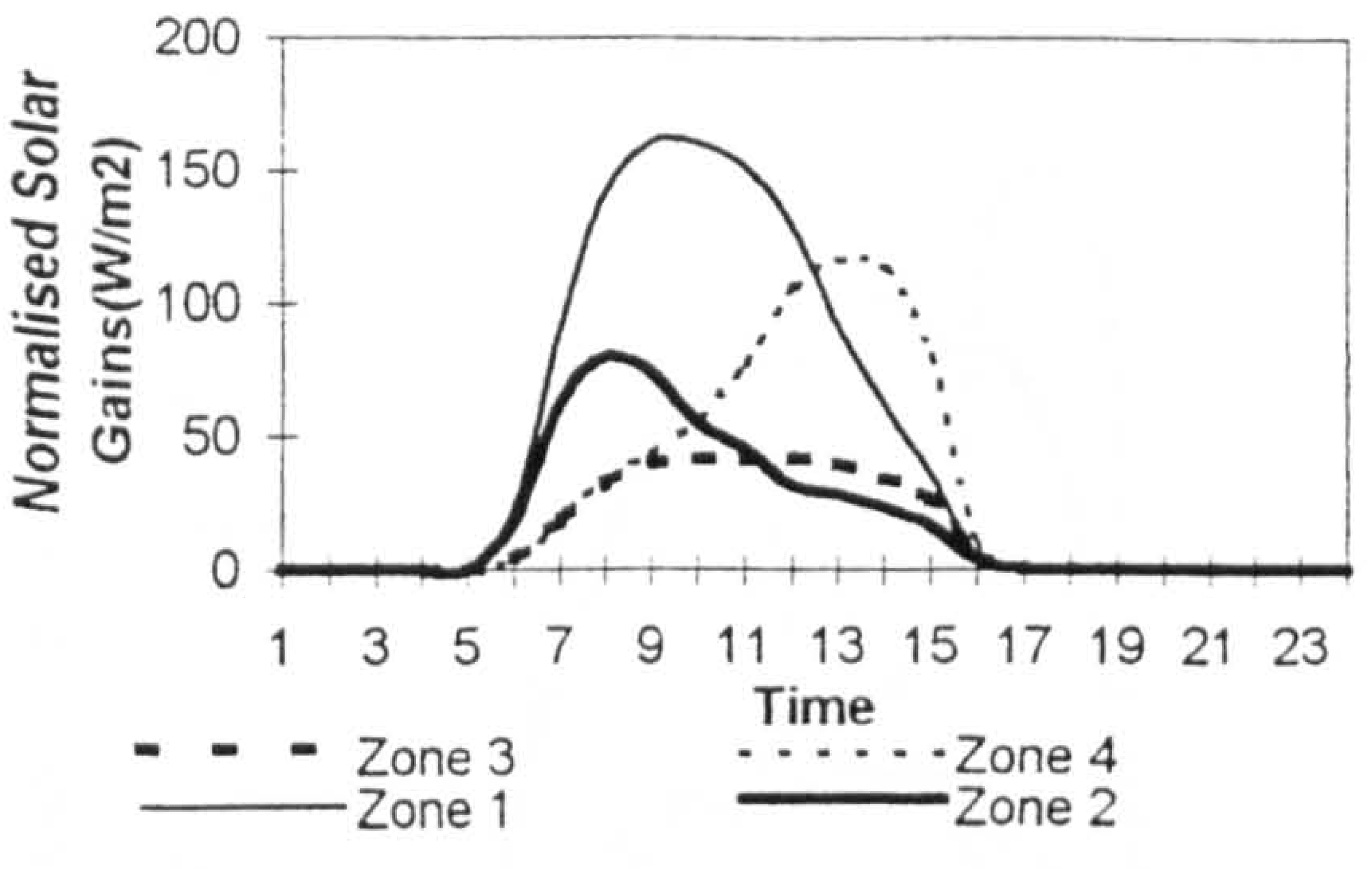


Figure 5.7.4a: Prestige Modern Building Solar Heat Gains with Sunshading

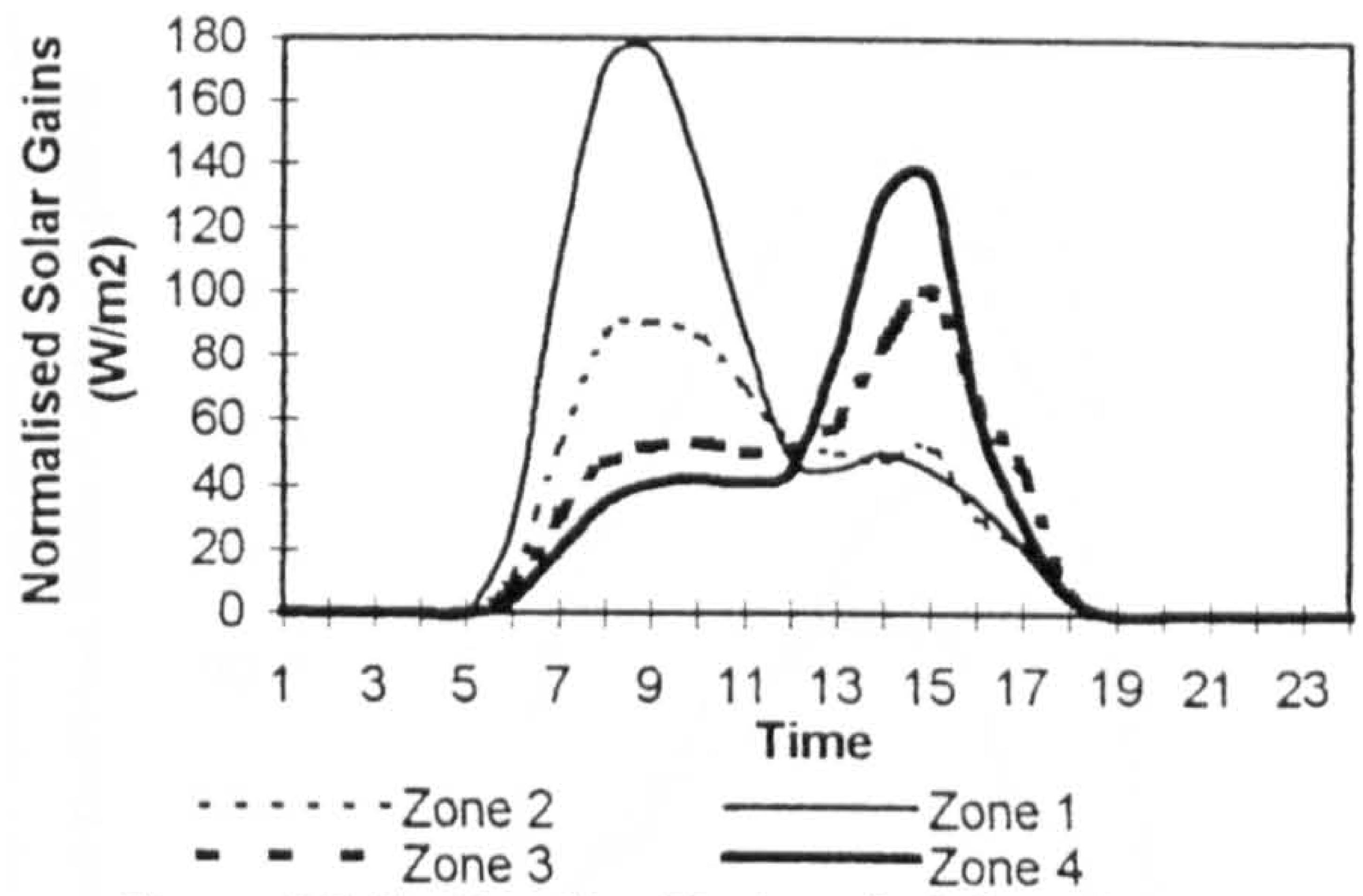


Figure 5.7.4b: Prestige Modern Building: Solar Gains in October with Sunshading

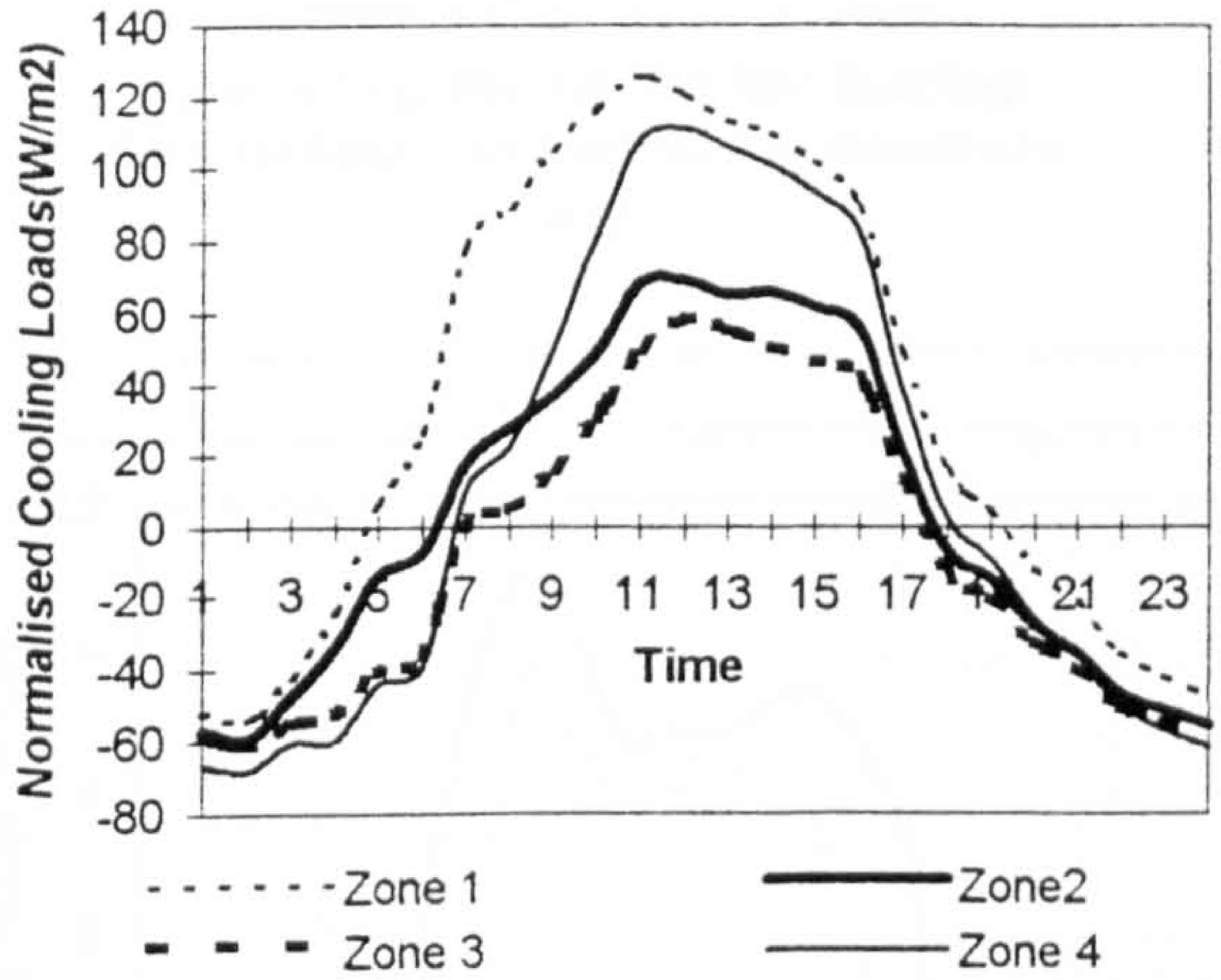


Figure 5.7.4c: Prestige Modern Building Cooling Loads in July with Sunshading

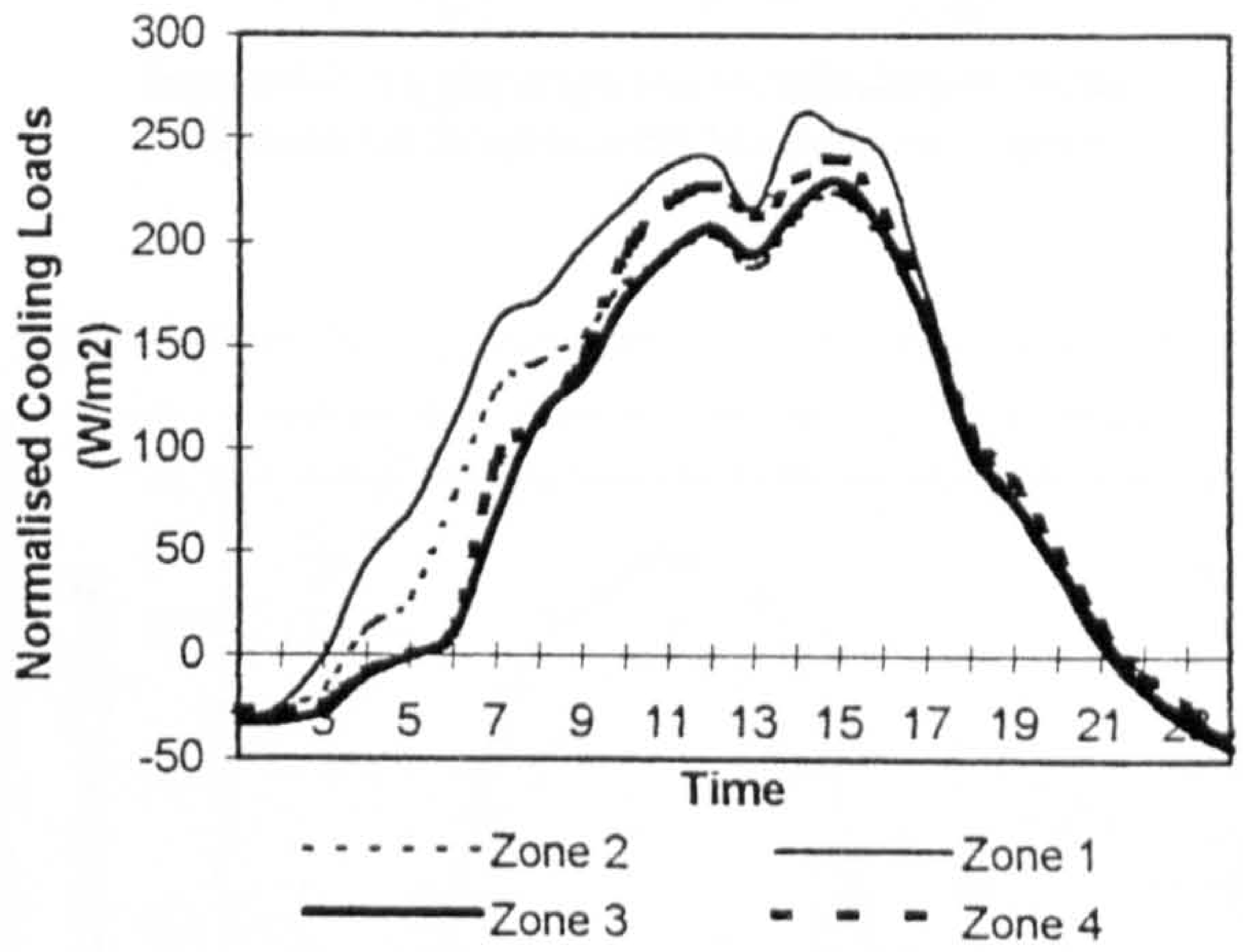


Figure 5.7.4d: Prestige Modern Building: Zone Cooling Loads in October with Sunshading

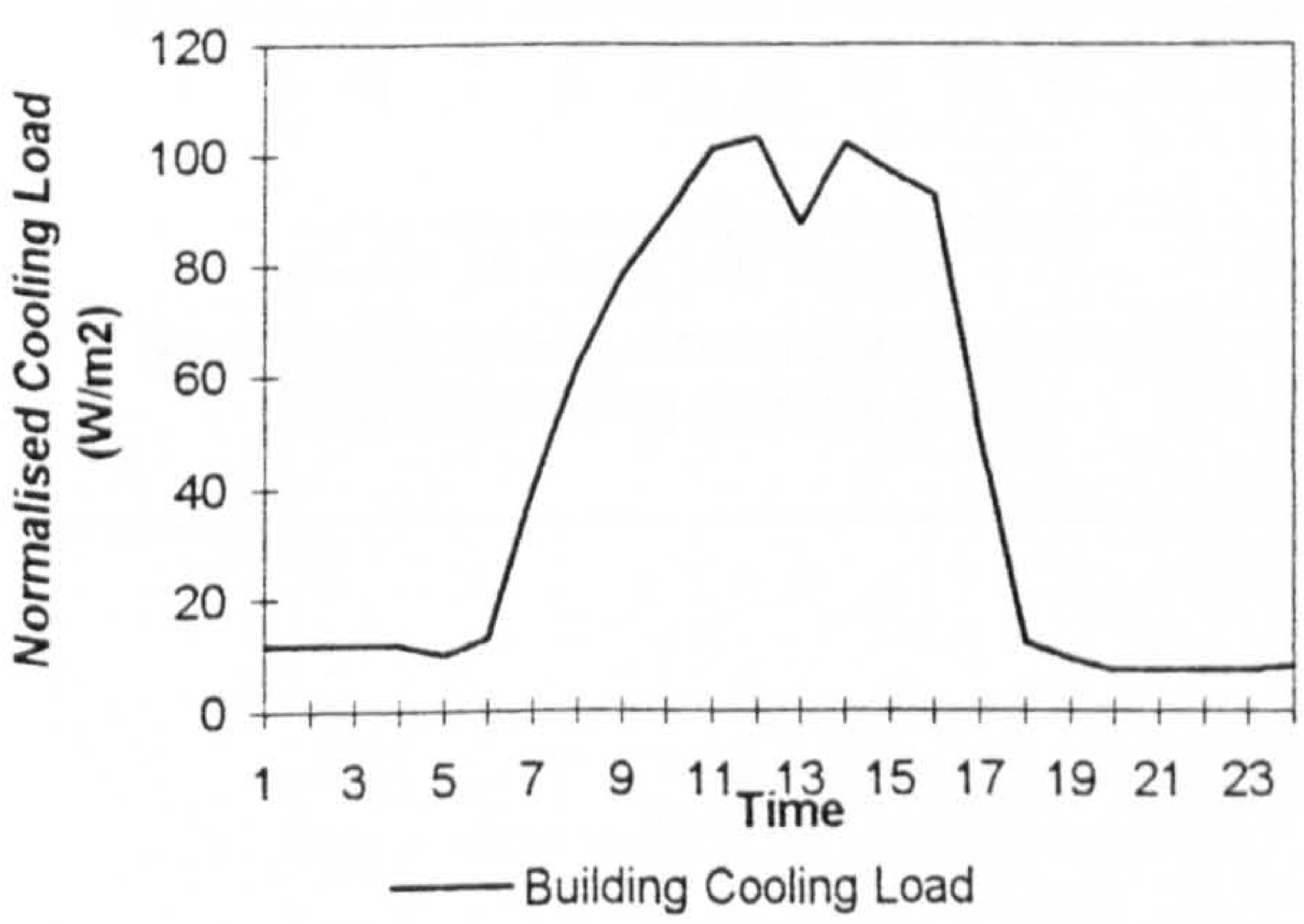


Figure 5.7.4e: Prestige Modern Building: Building Cooling Load in July with Sunshading

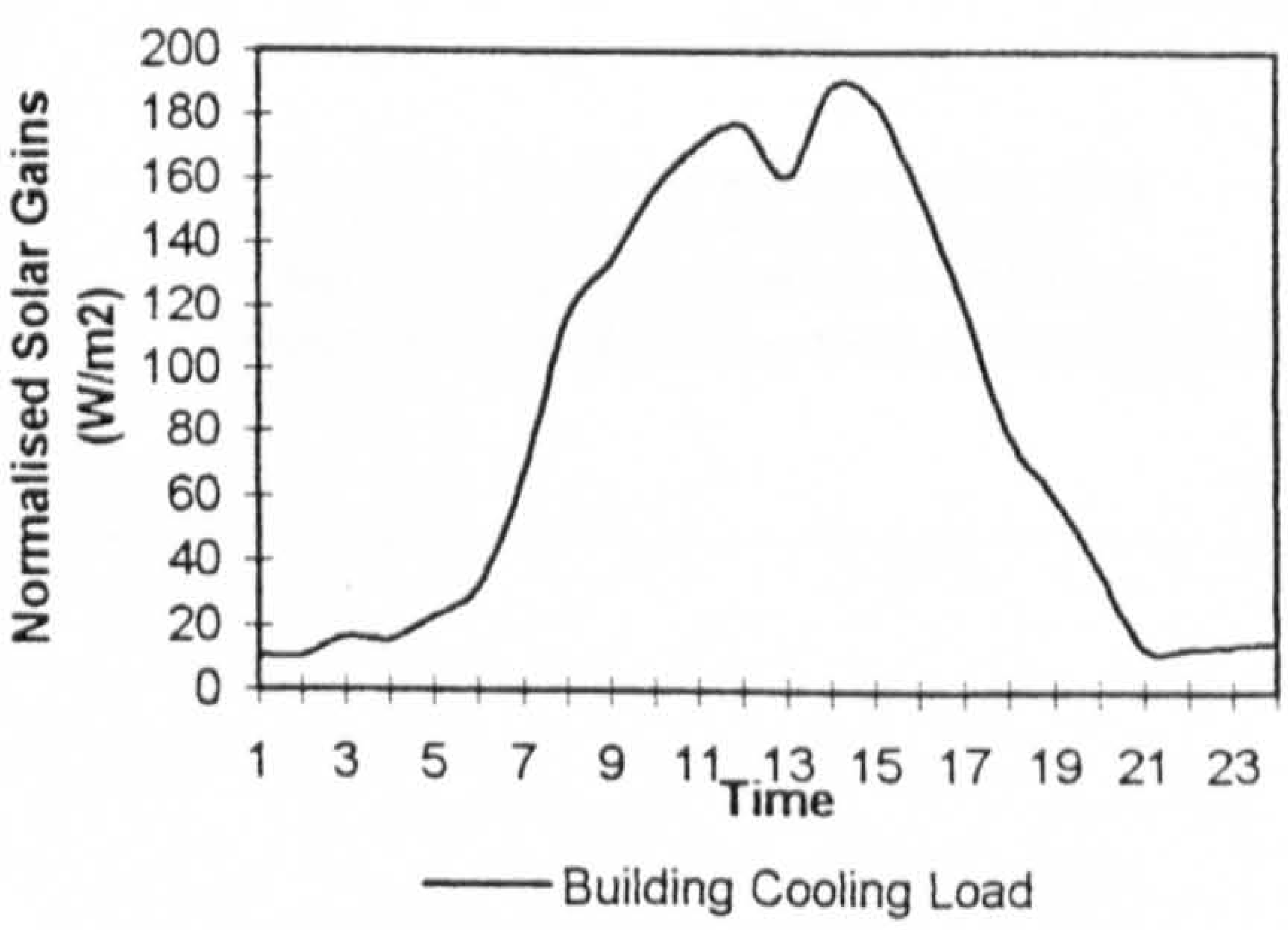


Figure 5.7.4f: Prestige Modern Building: Building Cooling Load in October with Sunshading

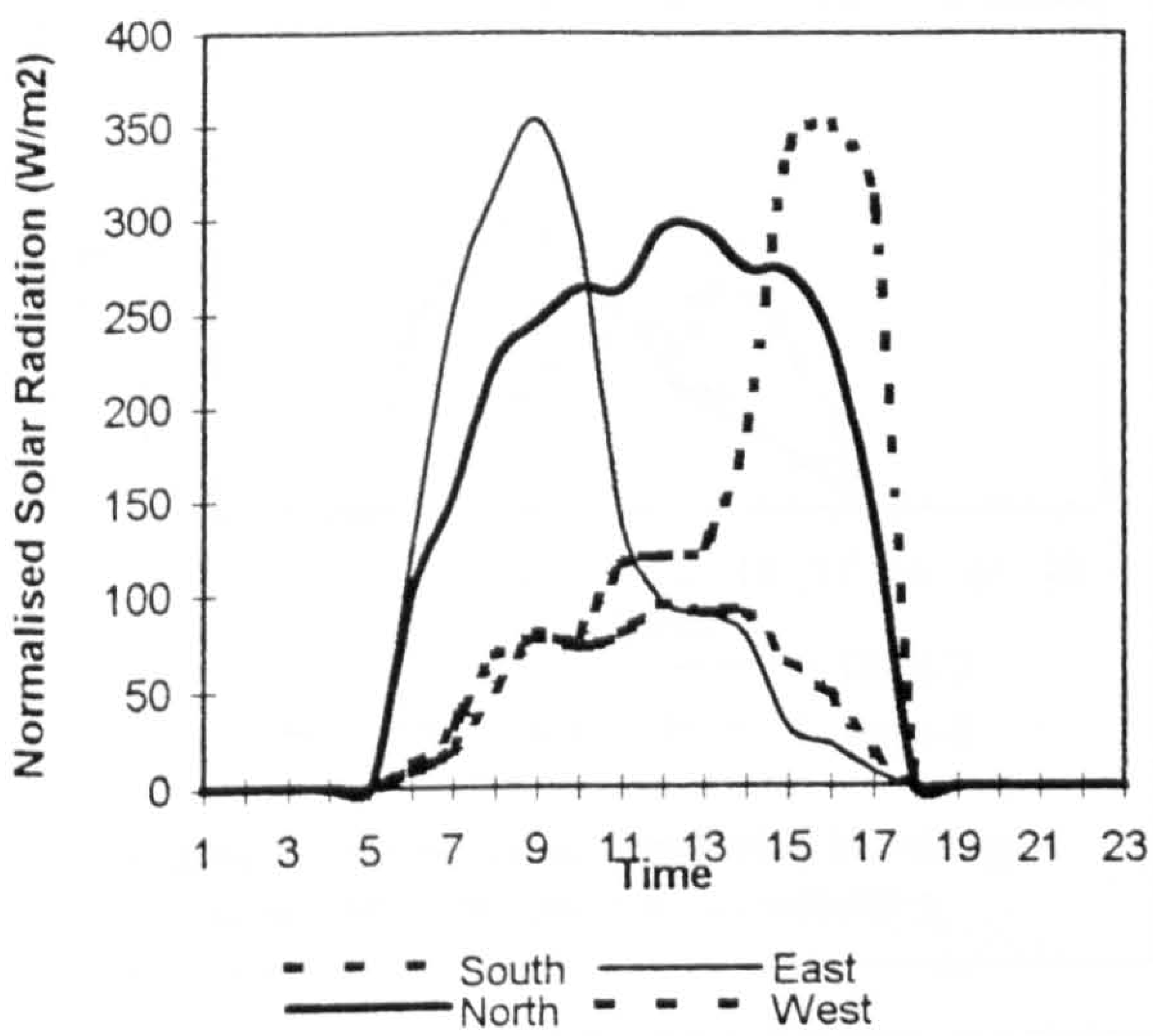


Figure 5.7.4g: Prestige Modern Building: Solar Radiation on Suntracking Modules in July

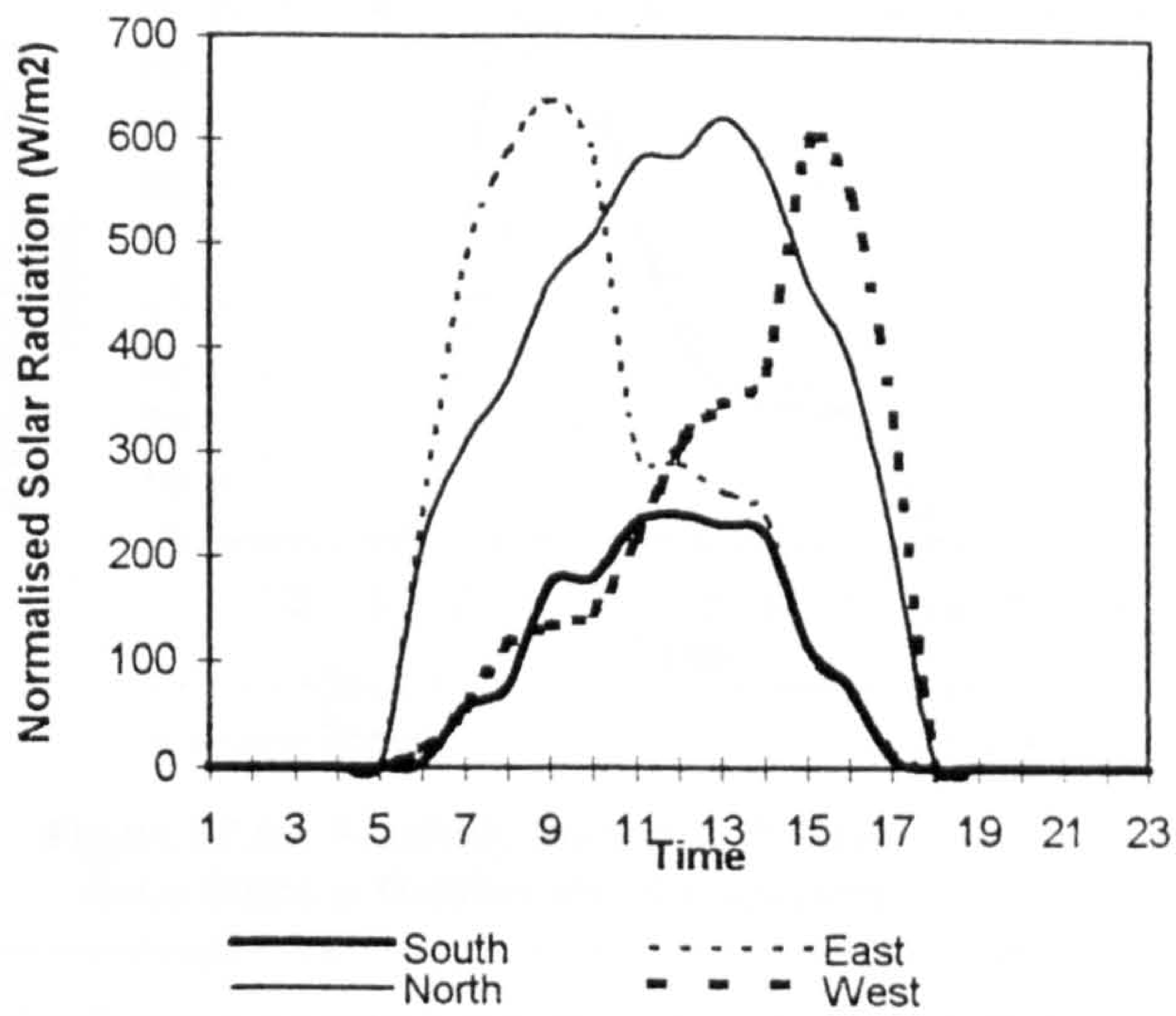


Figure 5.7.6h: Prestige Modern Building: Solar Radiation on Suntracking Modules in October

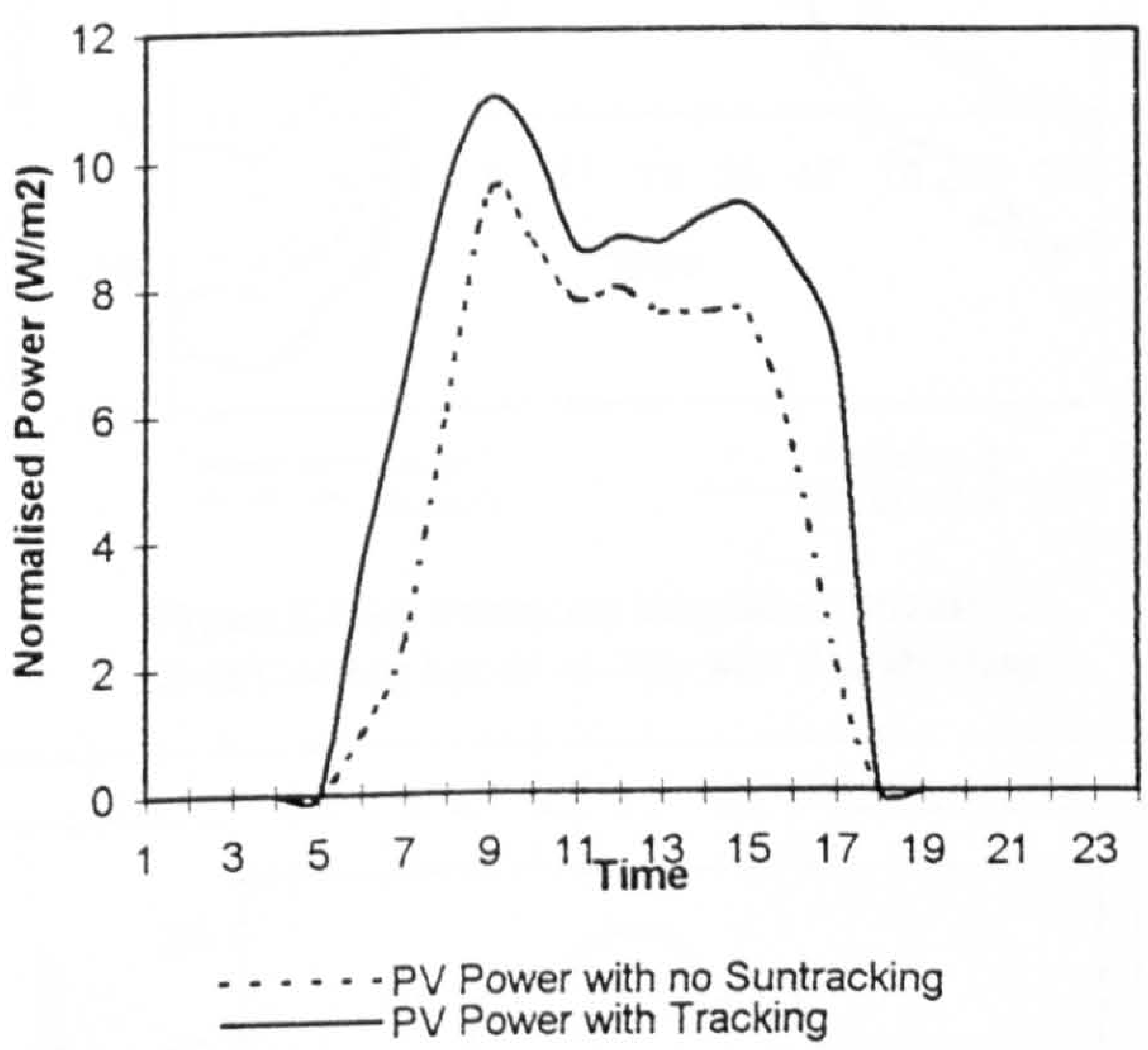


Figure 5.7.4i: Prestige Modern Building: Power fron Suntracking Modules in July

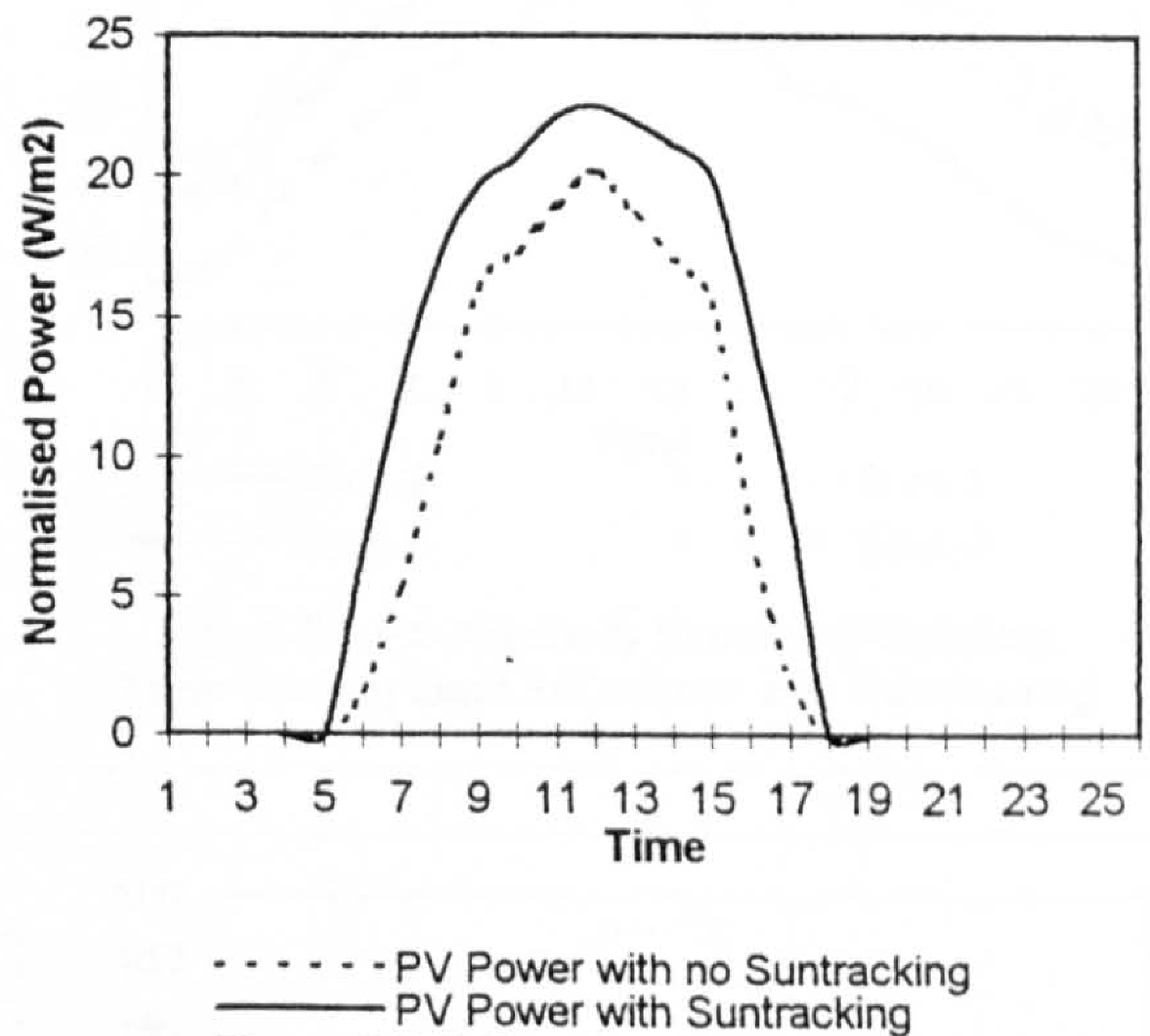


Figure 5.7.4j: Prestige Modern Building, Power from Suntracking Modules in October

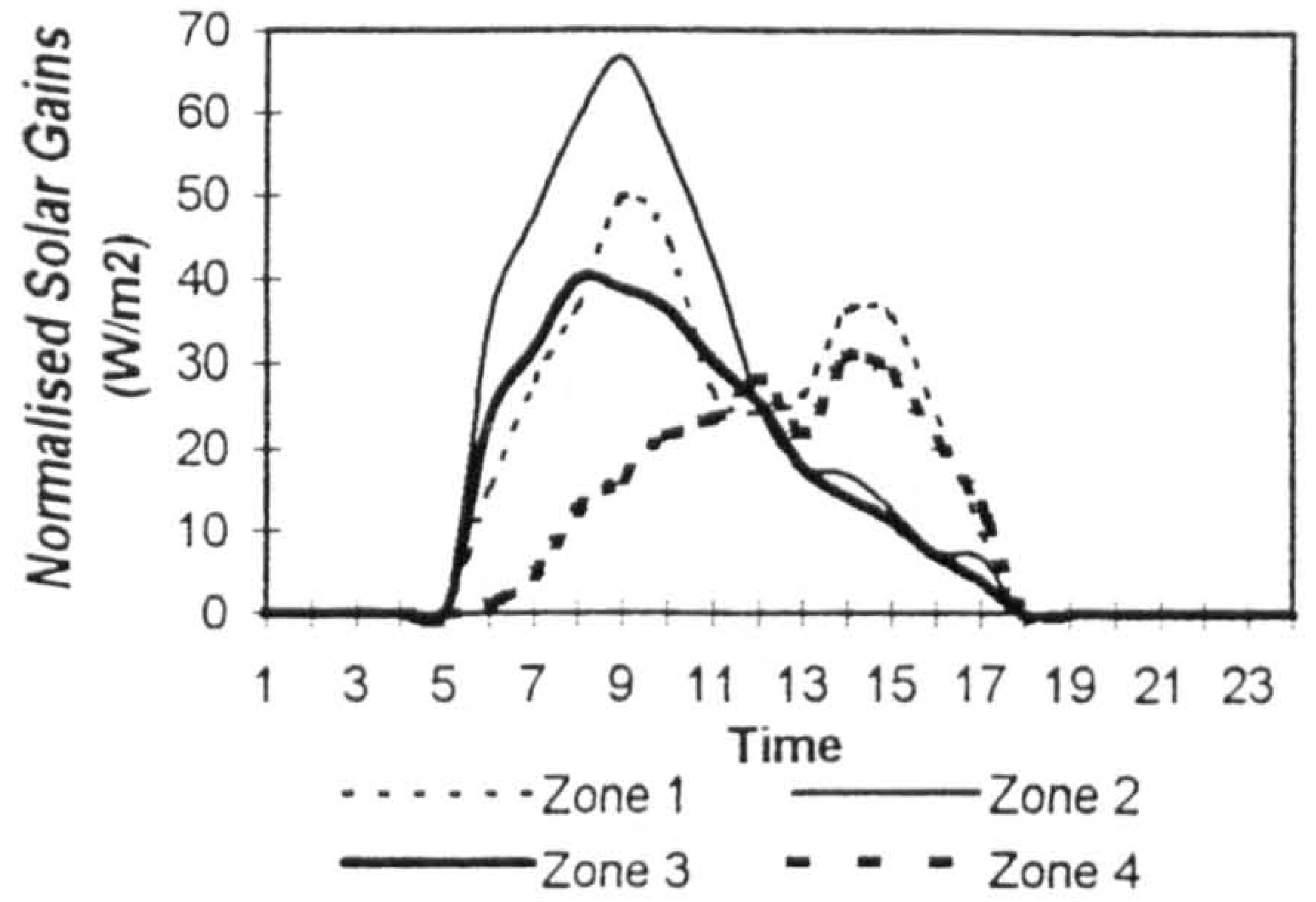


Figure 5.7.5a: Passively Ventilated Building: Solar Gains in July with Sunshading

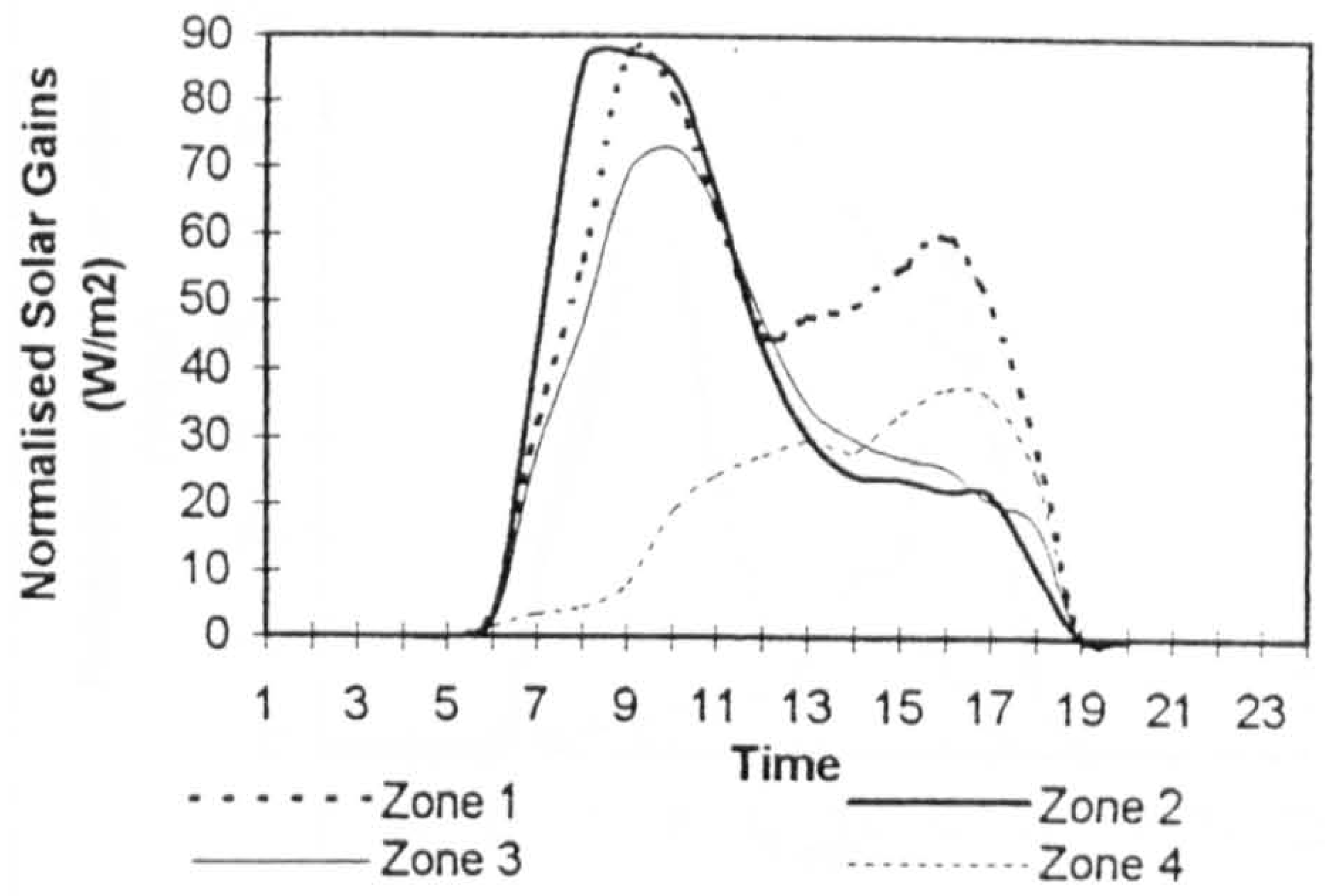


Figure 5.7.5b: Passively Ventilated Building: Solar Gains in October with Sunshading

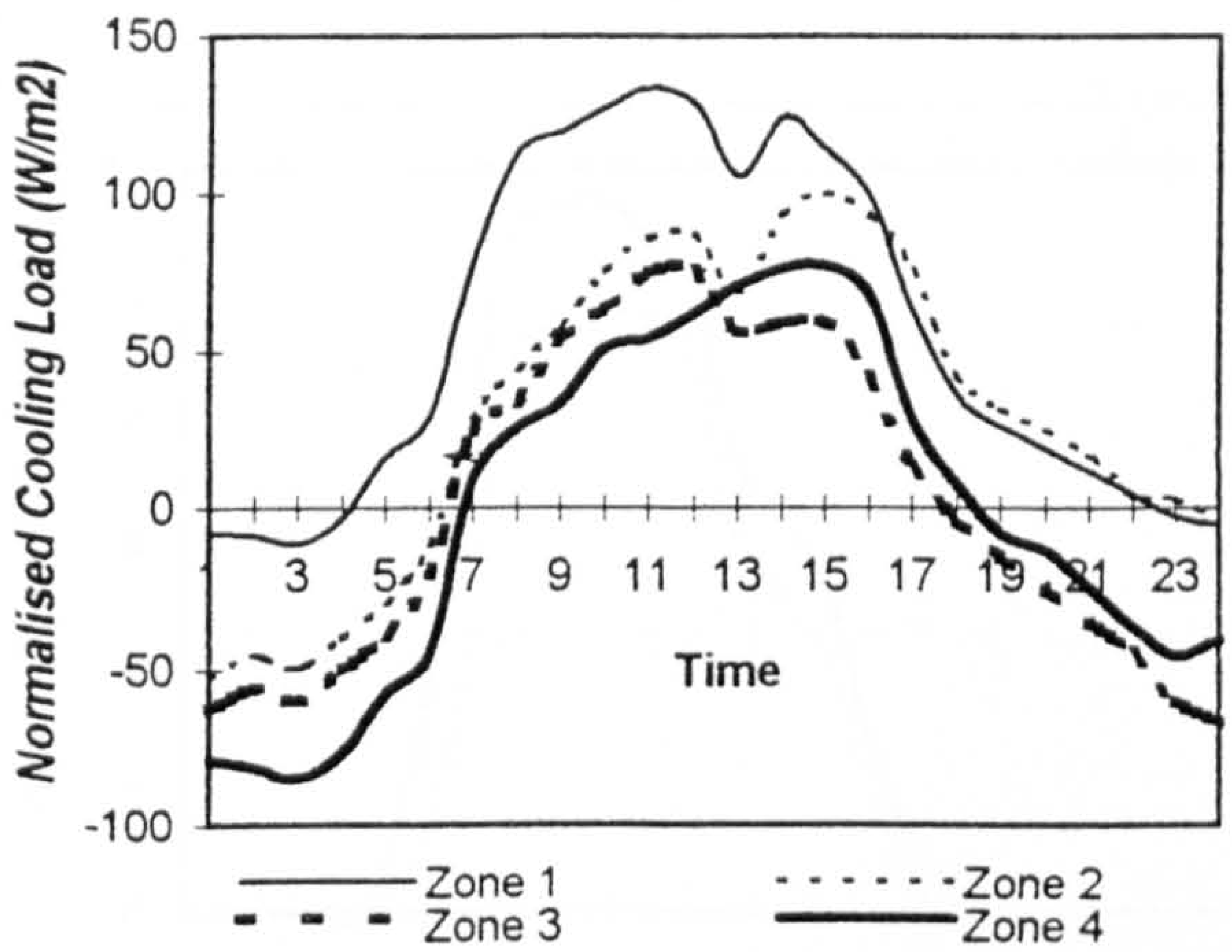


Figure 5.7.5c: Passively Ventilated Building: Zone Cooling Loads in July with Sunshading

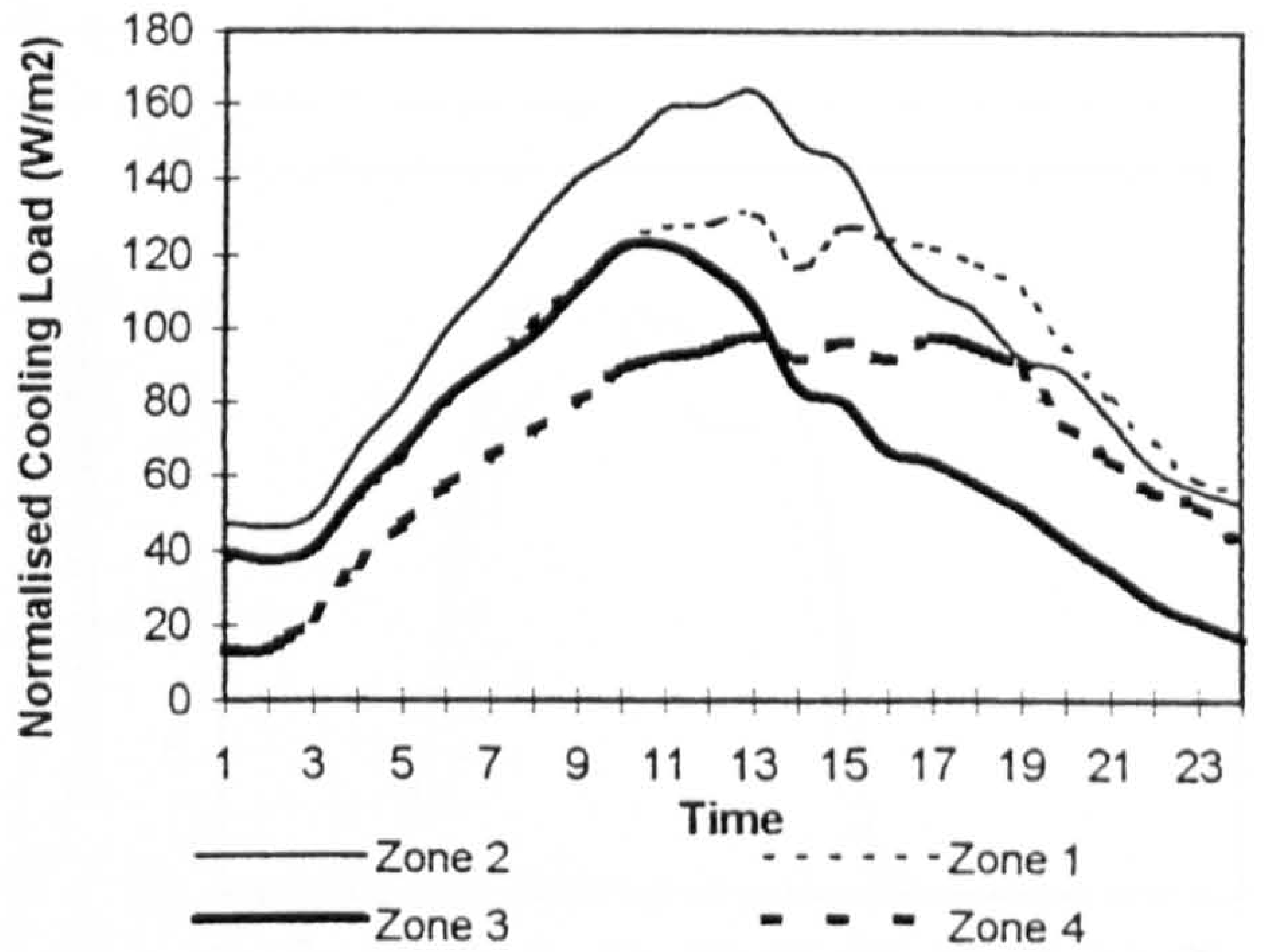


Figure 5.7.5d: Passively Ventilated Building: Zone Cooling Load in October with Sunshading

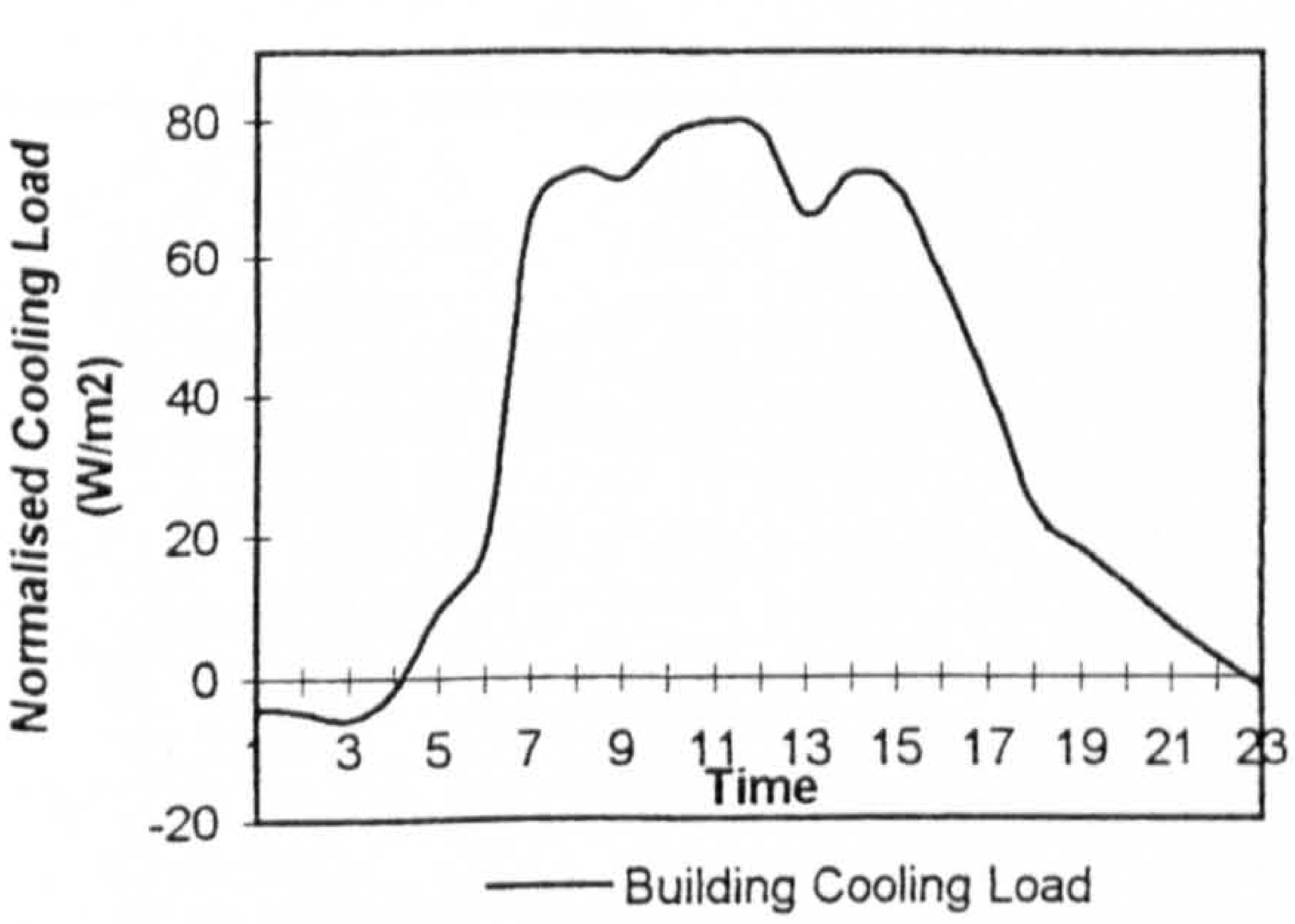


Figure 5.7.5e: Passively Ventilated Building: Building Cooling Load in July with Sunshading

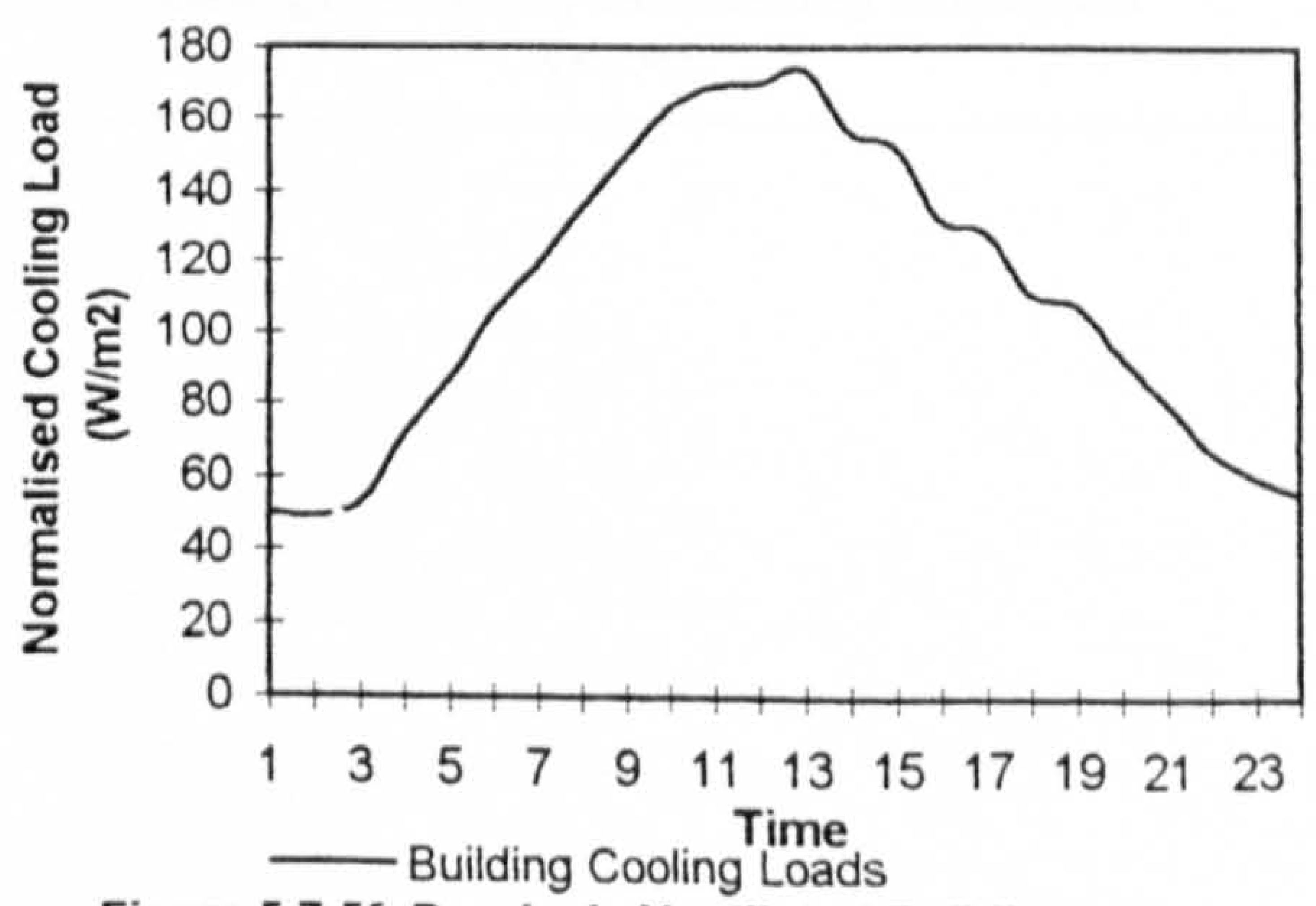


Figure 5.7.5f: Passively Ventilated Building: Building Cooling Load in October with Sunshading

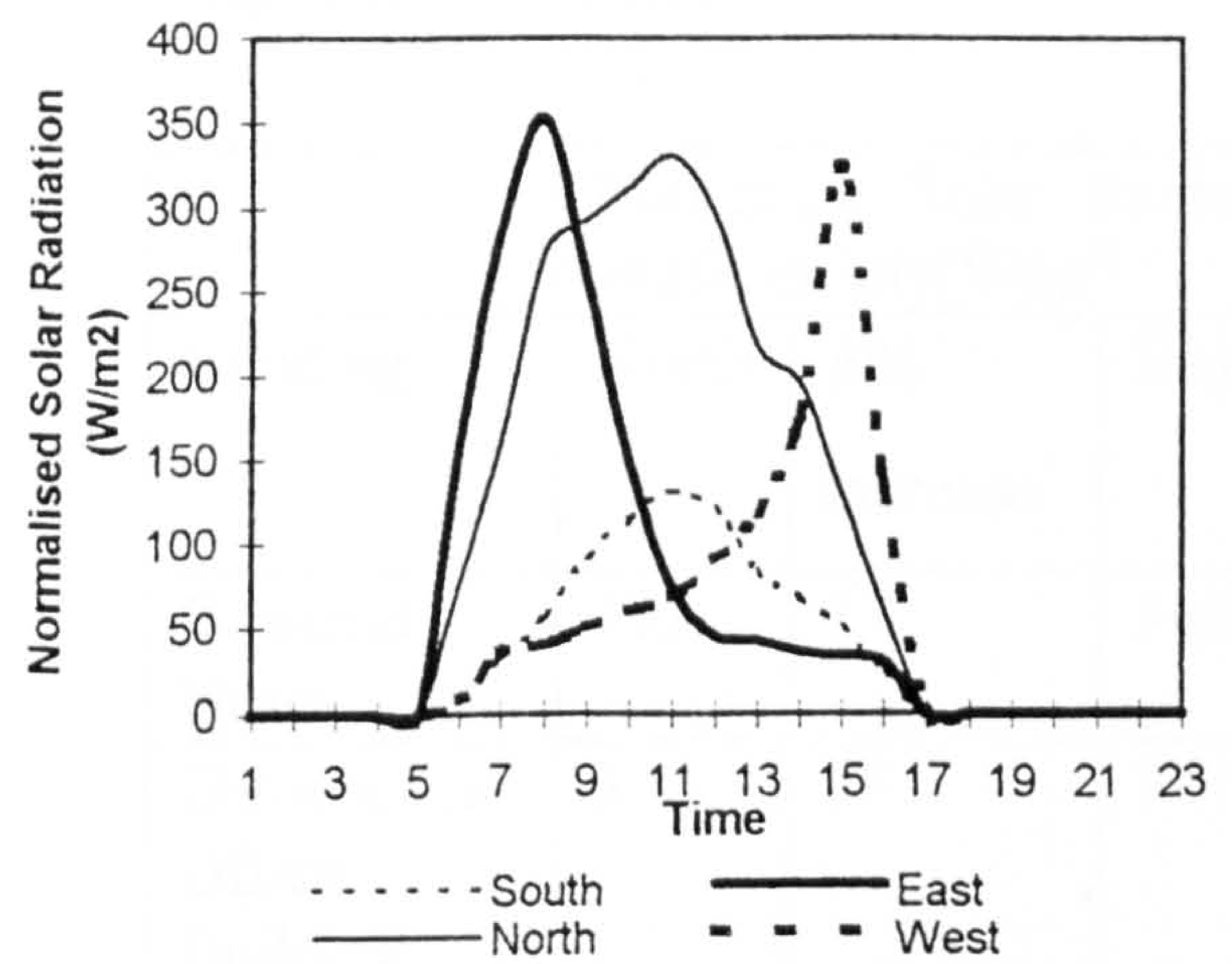


Figure 5.7.5g: Passively Ventilated Building: Solar Radiation on Suntracking Modules in July

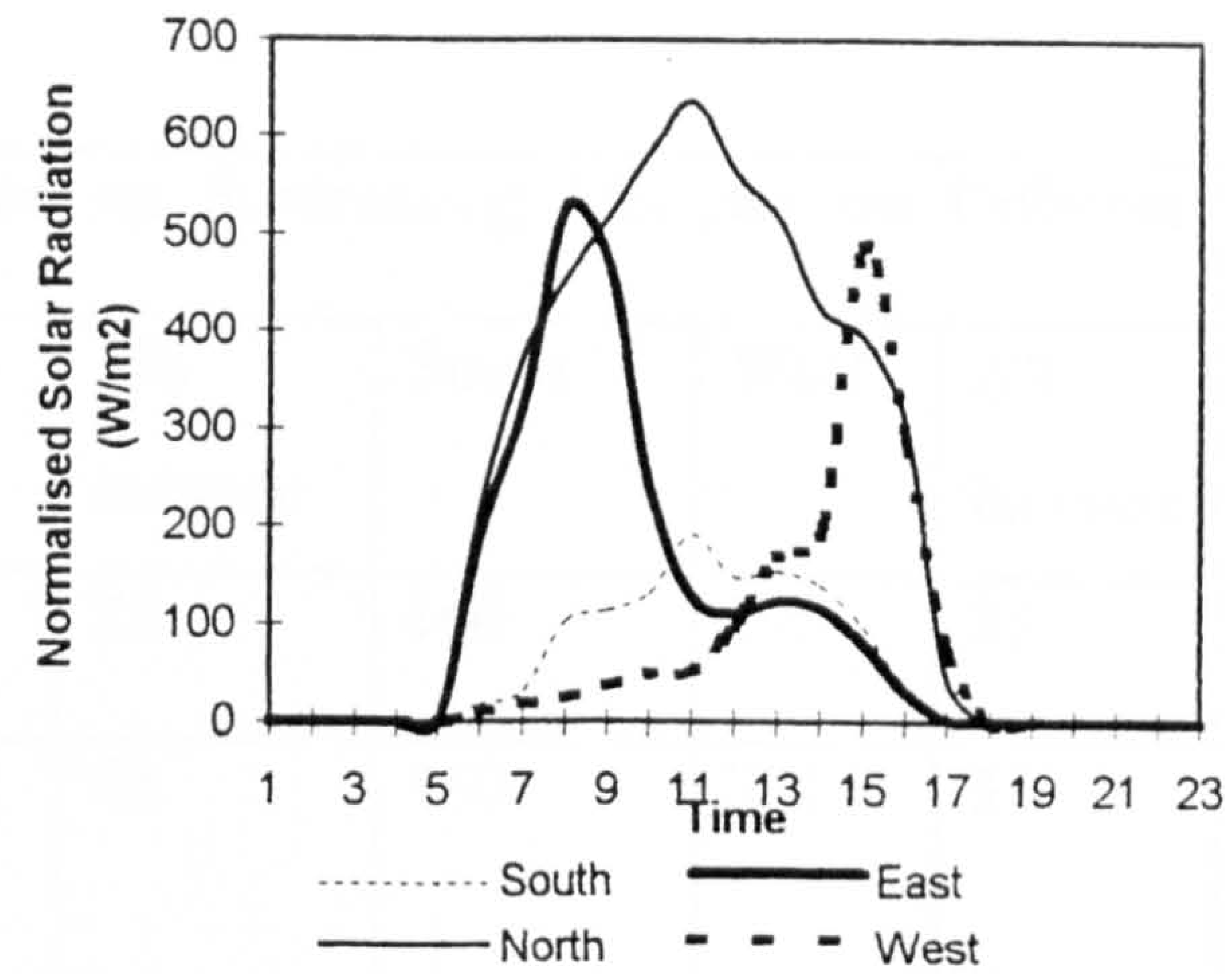


Figure 5.7.5h: Passively Ventilated Building: Solar Radiation on Suntracking Modules in October

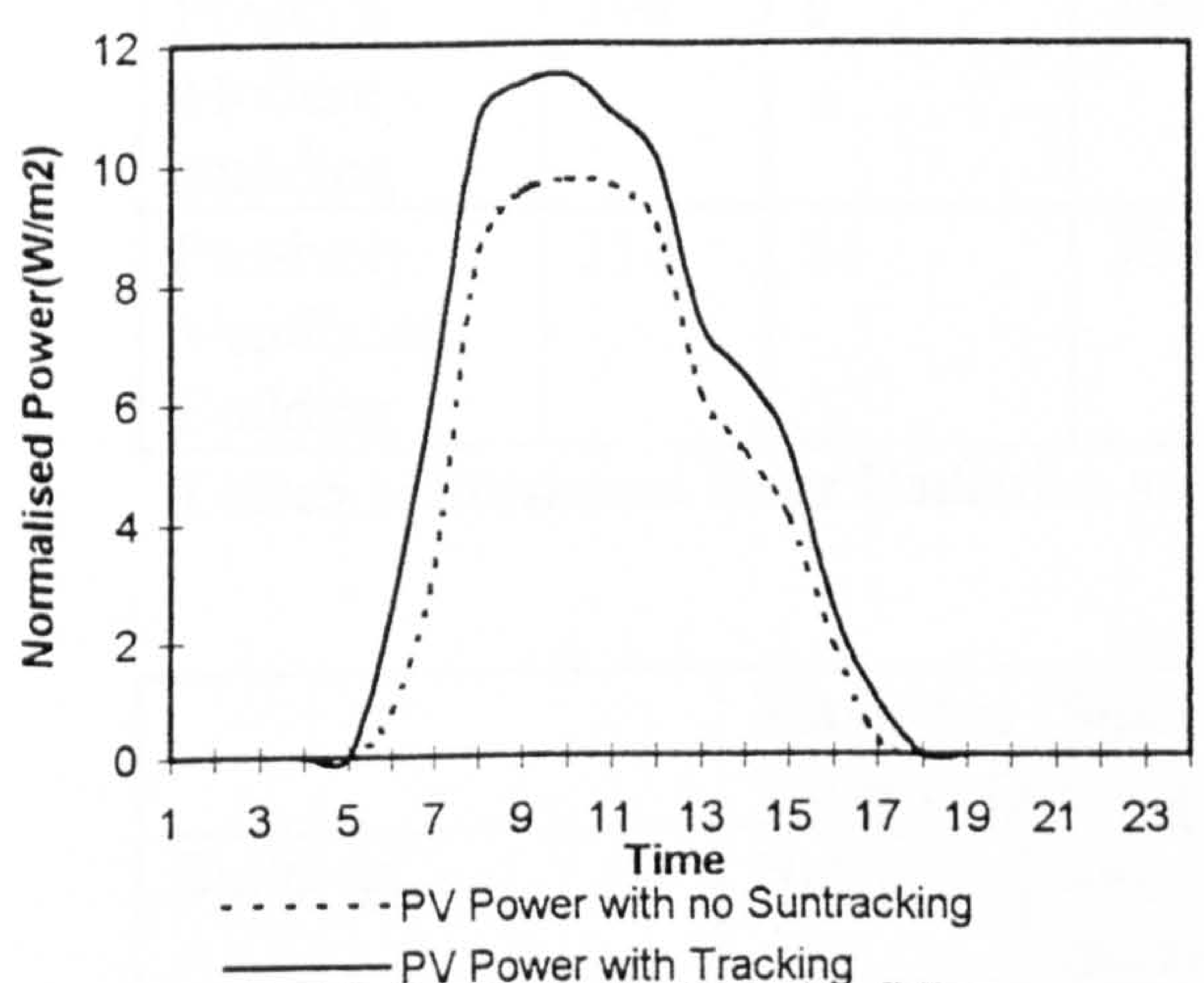


Figure 5.7.5i: Passively Ventilated Building, Power generated by Suntracking Modules in July

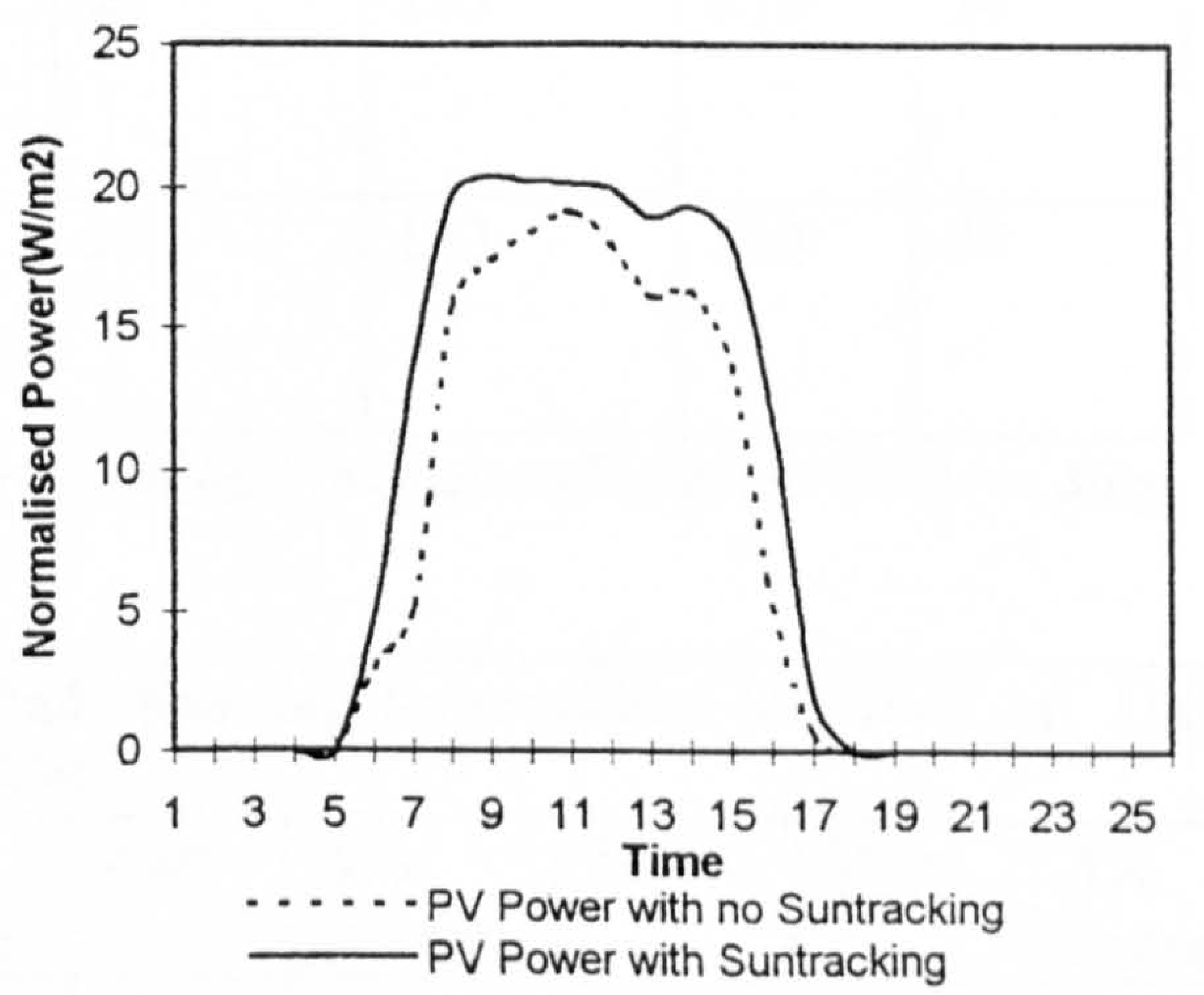


Figure 5.7.5j: Passively Ventilated Building, Power generated by Suntracking Modules in October

5.6 CONCLUSION

	Maximum Solar Radiation on Suntracking Modules on Different Walls in July(W/m^2)						
Building	North	Δ% increase	East	Δ% increase	South	West	Δ% increase
Business Hotel	335	21	340	23	160	295	35
Government Office Building	301	10	347	28	130	321	31
Tenant Occupied Building	330	12	320	19	158	320	32
Prestige Modern Building	298	9	353	26	113	310	34
Passively Ventilated Building	310	21	300	33	142	324	30

Table5.1: Maximum Solar Radiation on Suntracking Modules on Different Walls in July

	Maximum Solar Radiation on Suntracking Modules on Different Walls in October (W/m^2)						
Building	North	Δ% increase	East	Δ% increase	South	West	Δ% increase
Business Hotel	613	23	591	30	195	410	29
Government Office Building	639	20	571	35	260	460	24
Tenant Occupied Building	661	20	520	24	200	440	41
Prestige Modern Building	590	15	634	20	140	510	19
Passively Ventilated Building	637	19	529	24	155	418	17

Table 5.2 Maximum Solar Radiation on Suntracking Modules on Different Walls in October

Building	Max PV Output without suntracking W/m^2	Max PV Output with suntracking W/m^2	%age increase in PV output	Max Power Demand W/m^2	%age of PV output to Building Demand
Business Hotel	7	8	14	37	22
Government Office Building	9	10	11	23	43
Tenant Occupied Building	10	12	19	63	19
Prestige Modern Building	10	11	10	68	16
Passively Ventilated Building	9	11	22	25	44

Table 5.3: PV Output from Suntracking Modules on Different Buildings in July

Building	PV Energy without Sun-tracking Wh/m^2	PV Energy with Sun-tracking Wh/m^2	%age increase	Daily Energy Demand Wh/m^2	%age of PV output to Building Energy Demand
Business Hotel	45	58	29	544	11
Government	58	77	32	199	39
Tenant Occupied	69	88	27	503	18
Prestige Modern	73	101	38	790	13
Passively Ventilated Building	67	86	28	286	30

Table 5.4: PV Energy from Suntracking Modules on Different Buildings in July

Building	Max PV Output W/m² without Suntracking	Max PV Output W/m² with Suntracking	%age increase	Max Power Demand W/m²	%age of PV output to Building Demand
Business Hotel	21	25	20	59	41
Government Office Building	25	30	20	23	130
Tenant Occupied Building	26	33	27	145	23
Prestige Modern Building	20	23	15	150	15
Passively Ventilated Building	19	22	16	25	88

Table 5.5: PV Output from Suntracking Modules on Different Buildings in October

Building	PV Energy without Suntracking Wh/m²	PV Energy with Sun-tracking Wh/m²	%age increase	Daily Energy Demand Wh/m²	%age of PV output to Building Energy Demand
Business Hotel	137	193	41	938	21
Government	175	240	37	214	112
Tenant Occupied	145	200	38	1864	11
Prestige Modern	150	207	38	1797	16
Passively Ventilated Building	149	190	30	302	63

Table 5.6: PV Energy from Suntracking Modules on Different Buildings in October

Building	Maximum Solar Gains (W/m^2)				Maximum Zone Cooling Loads(W/m^2)			
	July		October		July		October	
		Δ% decrease		Δ% decrease		Δ% decrease		Δ% decrease
Business Hotel	110	38	105	50	43	26	113	14
Government	95	46	136	58	165	18	225	32
Tenant Occupied	63	34	73	56	80	48	225	25
Prestige Modern	149	26	181	47	125	17	270	21
Passively Ventilated Building	67	36	110	45	120	15	169	39

Table 5.7: Maximum Zone Solar Gains, Cooling Loads and Temperatures with Sunshading

Building	Maximum Building Cooling Zone			
	July	%age decrease	October	%age decrease
Business Hotel	50	14	68	31
Government	75	15	171	24
Tenant Occupied	74	13	182	16
Prestige Modern	103	12	183	25
Passively Ventilated Building	80	20	178	15

Table 5.8: Maximum Building Cooling Loads with Sunshading

When the PV modules are tracking the sun, the maximum PV output from the Business Hotel increases by an average of 14% in July and 20% in October. This increases its proportion of the maximum power demand to 22% and 41% respectively. The PV energy increases by 29% in July and 41% in October. This increases its proportion of maximum daily building energy to 11% and 21% respectively. The suntracking modules on the Government Office Building gives an increment of 11% to its maximum output in July and

30% in July. The proportion of the maximum PV output also increases to 43% in July and 130% in October. The daily PV energy increases by 32% and 37% in July and October, and improves the PV contribution to building energy demand to 39% and 112% respectively. The suntracking modules improves the maximum PV output by 19% and 27% in October respectively. This makes their proportion of the maximum power demand to be 19% and 23% respectively. The PV energy is also improved by 27% and 38% in July and October respectively. This gives an improvement of 18% and 11% to their proportion of daily building energy demand. In the Prestige Modern Building the suntracking modules improves the maximum PV output by 10% and 38% in July and October respectively. This improves its proportion to the maximum power demand to 13% and 15% respectively. The PV energy on the building also increases by 38% both in July and October respectively. This improves the proportion of the PV energy to the building energy demand by 13% and 16% respectively. The suntracking modules on the Passively ventilated module gives an increase of 22% and 30% to the maximum PV output in July and October respectively. This improves their proportion to the maximum building power demand to 44% and 88% respectively. The PV energy also increases by 28% and 30% in July and October. This improves their contribution to the building energy demand to 30% and 63% respectively.

Suntracking modules can actually take up all the power requirements of $25W/m^2$ of the Government Building which give $30W/m^2$, and 88% of the Passively Ventilated Building. There is also the possibility of exporting 12% of the generated energy on the Government Building. The proportion of the PV energy to the building energy demand of air-conditioned buildings is still low. However, there is further increase to this proportion because of the reduced power required for air-conditioning due to the shading effect of the suntracking modules as shown in Figure 5.7.1e and f, Figure 5.7.3e and f, and 5.7.4e and f. Table 5.8 shows that there is a decrease of 14%, 13% and 12% in the cooling load of the air-conditioning plants in the Business Hotel, the Tenant Occupied Building and the Prestige Modern Building in July. This is 31%, 16% and 25% respectively in October. This means that there is a potential for saving electricity by 15%, 10% and 14%

respectively in October when the air-conditioning system is usually on. There is also a potential for having smaller air-conditioning plants when the existing ones are replaced.

The output from a tracking system and an optimally tilted system on the north facing walls are usually comparable at noon. The increase in the maximum PV output on these walls are therefore less than those on the east and west walls. This is shown in Table 5.1 and Table 5.2. However, the modules on the north wall contribute most of the energy because their output improves by a factor of up to 40% in the mornings and afternoons as shown in Figures 5.7.1g and h to 5.7.5g and h. The north and south walls are also long on the Business Hotel, the Government Building and the Passively Ventilated Building. The modules on these therefore contribute up to 60%.

There are limitations in installing suntracking modules on the Prestige Modern Building. This is because the aesthetic appeal of the glass curtain and the plenum between it and the inside wall makes it impossible to have suntracking modules breaking its continuity. The best way to include them on this building is vertically integrated into the curtain wall. This greatly reduces the output. The Passively Ventilated Building has extension of the floors acting as overhangs. There is a limitation to how the modules will track the sun on the north wall because of these fixed overhangs.

Its is appreciated that tracking can only be used when there is a balance in the cost incurred in structural adjustments and the savings made from the extra power obtained. These results show that this balance can be achieved on some building, and the dual purpose of PV sunscreens definitely helps this balance to be achieved. The work done here used a state-of-the-art crystalline silicon module efficiency. The approximations made therefore gives amounts of power greater than those in most demonstration projects in existence. However, the work was done on the assumption that a high intensity procedure will have to be followed if the technology is to be successful.

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38. the system starts to behave much more like an open loop system.[38]

Chapter 6

The Economics of The Power Plant and The Status of The Zimbabwe PV Market

6.1 The Economy of The Building-Integrated PV Plant

Building-integrated photovoltaic power plants are high capital cost projects. This may reduce the motivation of private investors or public decision makers. Although there are many enduses for which photovoltaics is more cost effective than conventional supplies on a life cycle cost basis, the cost effectiveness of building integrated photovoltaics has never been fully justified on a direct comparison with conventional energy supplies. This therefore makes rational use of available funds, especially in developing countries involving concentrating on applications which give plausible economic advantages. In this research, the financial evaluation of the power plants considered is made so that the feasibility of such plants can be estimated. This evaluation is performed using the theory of cost benefit analysis on a life-cycle basis, also called Life Cycle (LCCA).

The economic assessment concentrates on

i. determining the unit cost of services provided by PV

The major assumptions made include

i. Taking a lifetime of 20 years which is generally accepted for both the PV plant and the building cladding system. The debt is then said to be fully financed for a debt term of 20 years. This can be done by a development agency or other financial institution.
ii. Discount rates are usually of the order of 10% for loans provided by development banks. The Hotel chain and the well established developer who owns the Tenant Occupied Building can borrow on the financial market with an 8% discount rate. On the other hand, the government can borrow from the World Bank using a 5% discount rate so that it can provide the PV power plant to its commercial building office.
iii. An inflation rate of 5% is also acceptable
iv. The BP85 solar modules are also assumed to be used in all the exemplar buildings

6.2 PV CLADDING COST

The cost of cladding systems varies significantly, and this most usually regards to: location of site, performance requirements, design life, material life, material selection, final design and detailing, size of building/cladding package, site layout, testing, procurement of materials, manufacturing process, cladding package requirements, transport, bulk/phased delivery, installation and maintenance requirements. Considering the mullion/transom system, the panel system, the rainscreen overcladding and the shading features the following costs can be considered.

System	Description	Cost(£/m^2)
Mullion/Transom Stick System	This framework with double glazing units as vision areas(non-opening) and insulated pressed sandwich spandrel panels(non-vision), K_{MTS}	400
Panel System	Factory made unitised panels, typically 4.3m high × 8.0m wide panel size. Built-in windows at say 30% of elevational area. Granite faced panel construction complete with internal lining, insulation, vapour barriers etc., K_{PS}	800
Rainscreen Overcladding	Polyester powder coated pressed aluminium panels hooked onto aluminium carrier rails. Rails bolted to an existing structure. Existing cladding repaired if necessary and thermal insulation upgraded, K_{RC}	300
Shading Features	Fixed and rotating aluminium blades attached to cladding , K_{SH}	200

Table 6.1 Costs of Cladding Systems

The cost of a solar cladding system /m^2

PV Cladding Cost = $C_{clad} + C_{pv} + C_w + C_{inv} + C_{panel}$

Cost of Solar Panels $C_{pv} = C_{pwp} * \eta * I/R_{ex}$

C_{clad} = cost of conventional cladding system

$C_{pv..}$= cost of PV module

C_w = cost of wiring

C_{inv} = cost of inverter

C_{panel} = cost of passive panel to be replaced by PV

C_{pwp} = cost per watt peak of solar modules

η_{mod} = solar conversion efficiency of modules

I = insolation at standard test conditions for solar modules

R_{ex} = exchange rate

In 1993 the wiring costs for a 80kWp array was estimated to be £35/m^2. However, an estimated wiring cost of £30/m^2 was considered more practical. Cost of inverters up to 100kW capacity are of the order of £500/kW falling to £300/kW$_p$ for large inverters. The £500/kW$_p$ was expected to fall linearly to £250/kWp by 2010. The cost of inverters varies over a wide range of prices dependent on size. If the inverter is sized according to the peak output of the array:, then its cost per unit area of cladding is sized according to the peak output of the array:

C_{inv} = inverter cost/kW * module efficiency

The cladding units and installation costs are expressed in cost m^2 of cladding, and the costs of the electrical system are related to the power level. The latter costs are then converted to costs per unit area using an appropriate power density.

Rain screen cladding manufacture(excluding PV laminates), K_{rc}	£225/m^2	
Fixings and bolts (5-10% of cladding manufacture)	£20/m^2	
PV laminates @ £2/W$_p$ and an overall value of 102W$_p$/m^2	£202/m^2	
PV laminates per unit cladding area, K_{pv}	£150/m^2	
(The laminates occupy 0.75 of the cladding area)		
Labour, K_{lab}	£30/m^2	
Total Cladding System		£425/m^2
Inverter , K_{inv}	£0.30/W$_p$	
Wiring(including labour), K_{wr}	£0.29/W$_p$	
Total Electrical System	£0.59/W$_p$	
Total Electrical System with Overall value of 102W$_p$/m^2		£60./m^2
Total PV Cost		£485/m^2

Table 6.2 PV Cladding per unit area at U$3/W$_p$

Material costs of cladding systems exceed those of simple vertical system, due to the additional fabrication required to form the aluminium support system for the PV laminates and the requirement for soffit panels for the inclined units.

A vertical rainscreen system would have reduced the unit area cost to £362/m^2 due to a reduction in material cost of the cladding element (£162 cf. £225/m^2), although it should be noted that there would be less installed capacity for the PV system and fewer aesthetic benefits. For fully developed vertical system installed after 2005, the achievable costs are as follows (in present day values)

Rain screen cladding manufacture(excluding PV laminates), K_{rc}	£115/m^2	
Fixings and bolts (5-10% of cladding manufacture),	£15/m^2	
PV laminates K_{pv}	£150/m^2	
Labour, K_{lab}	£30/m^2	
Total Cladding System		£310
Inverter, K_{inv}	£0.30/W$_P$	
Wiring(including labour), K_{wr}	£0.20/W$_p$	
Total Electrical Cost	£0.50/W$_p$	
Total Electrical Cost with an overall value of 102W$_p$/m^2		£51/m^2
Total System Cost		£361.40/m^2

Table 6.3 PV Cladding Cost with reduced prices on other components

To meet target figures of the electricity cost from PV integrated into buildings of say £0.10/kWh, then significant cost reductions are still required for both the solar modules and associated equipment. The cost can be reduced using methods of integrating PV laminates into cladding elements and reductions in hardware and labour associated with the electrical installation.

The PV cladding costs considered above, are much smaller than that used for the Northumberland building (of £907/m^2), because the cost of the laminates was £4/W$_P$ (US\$6/W$_p$) as compared to £2/W$_p$ (\$3/W$_p$) which is now anticipated. The wiring costs were also high at £1/W$_p$, because the wire had to be stripped to be connected to the modules, which is labour intensive. However, plug-in cables reduces the wiring costs to £20/W$_p$. This cost reduction together with module inverters is expected to reduce the electrical cost to 50p/W$_p$. This is also expected to fall further to 25p/W$_p$. On the Northumberland Building project, if the building project as a whole is considered, the incorporation of PV may add as little as 2% to the overall construction cost. A total surface area of cladding of about $390m^2$ give a total system cost of £354,000. With an estimated annual output of 30,000kWh and a lifetime of 25years this gives an electricity of 0.47/kWh.

6.2.1 Tenant Occupied Building

This building is owned by the biggest building developing corporation in Zimbabwe, and in the event that it wants to retrofit the building, they can borrow money from the financial market with a discount rate of 8%. This building has an estimated cost of £20 million of which £2million was spent on the air-conditioning and ventilation system, and another £30,000 per annum is required for running cost. About 35% of the cooling load is due to solar gains through the windows. Since around 50% of the solar gains is reduced through shading with PV sunscreens as shown in Chapter 4, it follows that there is a 16% reduction of cooling load that the air-conditioning plant has to take up. If in future when the building is being retrofitted a consideration of the shading system which uses PV panels have to be reconsidered. This would mean a smaller air-conditioning system which would cost 16% less can be installed. This would make a total amount of

$0.16 \times £2,000,000 = £320,000$ savings on the system, and also

$0.16 \times £30,000 = £4,800$ per annum savings on running costs

This can contribute to the income for financing the building integrated PV system.

There are 17 rows of 1.5 metres height and covering 116 metres of the perimeter. This gives an area of: $17 \times 1.5 \times 116 = 2958m^2$

Using the cost of rainscreen cladding considered above

The total cost of installing the PV system covering all the available cladding area is

$2958m^2 \times £485/m^2 = £1,435,000$

The system can provide 520,000 kWh per year

The lifetime of a PV plant can taken to be 20 years. The cost of electricity can be estimated as: $£1,876,000 \div (520,000kWh/year \times 20 \text{ years}) = £0.14/kWh$

If the PV cladding cost estimated in Table 6.3 is used then the total plant system will cost

$2958m^2 \times £361/m^2 = £1,068,000$

The cost of electricity will therefore become £0.10/kWh

However, more considerations need to be taken into account:

ECONOMIC PARAMETERS				*Calculations*
Parameters	Symbol	Quantity	Units	
Period of Analysis	n	20	years	
Discount Rate	d	0.08		
Inflation Rate	h	0.05		
Discount Factor	a	0.972		a=(1+h)/(1+d)
Annualisation Factor	Pa(n)	15.1		$Pa(n)=a(1-a^n)/(1-a)$
SYSTEM SPECIFICATION				
Annual Load met	La	520,000	kWh/year	
PV System Array Size	P_{pv}	360	kW_p	Area(A) =$2958m^2$
COST DATA				
Capital Cost				
PV Laminates	C_{pv}	443,700	£	$C_{pv} = K_{pv} \times A$
Rainscreen Cladding	C_{rc}	665,550	£	$C_{rc} = K_{rc} \times A$
Fixings and Labour	C_{lab}	147,900	£	$C_{lab} = K_{lab} \times A$
Inverter/Wirimg	$C_{inv/wr}$	151,000	£	$C_{inv/wr} = (K_{inv} + K_{wr}) \times 136 \times A$
SUB-TOTAL	C_{cap}	1,408,000	£	
O&M Costs	R_{om}	37,500	£/year	$R_{om} = 0.02 \times C_{pv}$
Life Cycle O&M Costs	C_{om}	566,600	£	$C_{om} = R_{om} \times Pa(n)$
Income due to air-conditioning savings	$C_{a/c}$	-320,000	£	
Income from savings on conventional cladding	C_{rc}	-222,000	£	$C_{rc} = (K_{RC} - K_{rc}) \times A$
Income due to demand saved on a/c due to shading	C_{shd}	-372,000	£	Starting off with £4,800 for 20 years, and increasing 20% p.a. until price is £0.10/kWh
Total Cost	C_{tot}	1,136,000	£	
ECONOMIC INDICATORS				
Total Life Cycle Cost	LCC	1,136,000	£	$LCC = C_{tot}$
Annualised LCC	ALCC	75,200	£	ALCC = LCC/Pa(n)
Levelised Energy Cost	Ke	0.14	£	ALCC/La for over 20 years

Table 6.4 Economics of The PV Plant on a Retrofitted Tenant Occupied Building

6.2.2 Cost Of Solar Electricity

Considering the economics of PV cladding systems includes :

taking into account the money recouped from the electricity produced by the PV array.

the cladding system lifetime, N is taken as 20 years

assuming no storage ie the electricity generated by the cladding system is used by the host building or is sold back to the utility grid .

Operational and maintenance are assumed to be negligible since they are at present unquantified

The price charged for the electricity generated by the cladding system is calculated as follows

$$P_e = \frac{C[d(1+d)^N}{E_o[(1+d)^N - 1]}$$

where the capital cost of PV,

$$C = C_{PV} + C_W + C_I + C_{panel}$$

and E_o is the electricity generated by the building. The cost of the passive panel to be replaced by PV, C_{panel} is subtracted from the overall cost of the system since this is taken to be an avoided cost. The capital expenditure of the PV array, C is the extra cost over and above that which would have been paid for a conventional cladding system.

Effective Efficiency	Inverter		Wiring		Overcladding			Labour	Cost	Price
					Passive	PV				
	£/kWp	£/m²	£/m²		£/m²	£/Wp	£/m²	£/m²	£/m²	£/kWh
14%	500	70	30		220	2	280	30	630	0.36
14%	420	59	30		220	1.66	232	30	571	0.33
14%	333	47	30		220	1.33	186	30	513	0.27
14%	250	35	30		220	1.00	140	30	455	0.25

Table 6.5: Cost of Electricity

6.2.3 Discussion on PV Cost

The main areas of focus are on the reduction in the cost of PV, the reduction in the cost of inverters, the labour requirement and the passive part of the overcladding. The reductions achieved through this should be substantial as shown above.

The recent value of commercial building power is about £0.02/kWh in Zimbabwe. This is because it is government owned and therefore this price has been subsidised. However, the decision to privatise the power utility has seen the power tariff being increased two times in the past year, with an effective increase of 20% each time. This increment is expected to be higher this year, and it is focused that the price will become £0.10/kWh in 2010. This is a target that can be met by PV generated power from calculations using the cladding cost from Table 6.3.

However, without considering savings due to the replaced cladding, those due to reduced energy demand for air-conditioning and those due to a smaller air-conditioning plant because of reduced cooling load as a result of the shading effect of the PV modules, the cost of electricity would be 2.5 times more expensive at 25p/kWh, as shown in Table 6.5. Table 6.4 clearly shows one way of financing the PV systems by replacing conventional wall systems with the PV laminates. For instance, the glass curtain wall on the Prestige Modern Building costs around £600/m^2. By replacing them with PV cladding on the non-visual areas would result in £115/m^2 being saved. Taking an area of 80m length around the building, and 1.5m height of replaced curtain wall over 21 floors. It follows that the total saving made is: 21floors × 80m × 1.5m × £115/m^2 = £289,000.

6.3 Effects of The Commercial Building PV Market on The National Market

The work done in this research is unique in that it seeks to establish a way of indirectly assisting the photovoltaic technology in Zimbabwe. This work can be called finding an engineering solution to a financial problem, because it identifies ways by which through integrating existing engineering methods more capital can become available for PV technology. Establishing the potential of photovoltaics in the commercial building market assists the technology in operating from a high capital base which would not only increase the volume flow of the technology, but also improve reliability and most importantly stimulate the establishment of sustainable financial mechanisms which can be spread to the all parts of the market.

The building integrated PV market has to operate in conjunction with some of the PV systems that already exists in Zimbabwe. The existing market has made a foundation for PV in Zimbabwe by allowing the technical know how to be developed. However, the installed capacity has been limited. The use of solar home systems is a major thrust in aid-agency and national government funding around the world. There are many excellent reasons for this, as discussed in Chapter 1, but there is a tendency for PV to be regarded as a 'poor man's technology' used in poor countries. The large building-integrated PV programmes in Japan and the USA counter the view that PV is only for the Third World. In Africa PV the wide view that PV is a technology for the rural poor not helpful because no one wants a 'poor man's technology': not the rich and particularly not the poor if they can help it.

The development of a market for PV on buildings in Zimbabwe would change the image of PV for the whole of society and it would help to promote PV as an urban and rural power supply option. The consideration of seeking ways to bring more local capital into the PV technology is a natural next step in the evolution of Zimbabwe as a potential major market for PV . This can be best understood by considering the installed capacity and the nature of the projects that have been carried out to date in the Zimbabwe. The PV projects in Zimbabwe have traditionally been funded by international donors such as UNDP, DANIDA, NORAD, USAID AND GTZ. It is expected that these projects act as springboards on which local expertise and resources are identified and used in future on a more sustainable basis.

6.4 The Installed Capacity of Photovoltaic Systems in Zimbabwe

In 1991 the installed capacity of PV in Zimbabwe was estimated to be 151 kW_p and consisted of 2500 systems[1]. The proportion of this capacity for each type of user, use and size were as shown in Figure 6.1, Figure 6.2 and Figure 6.3 respectively.

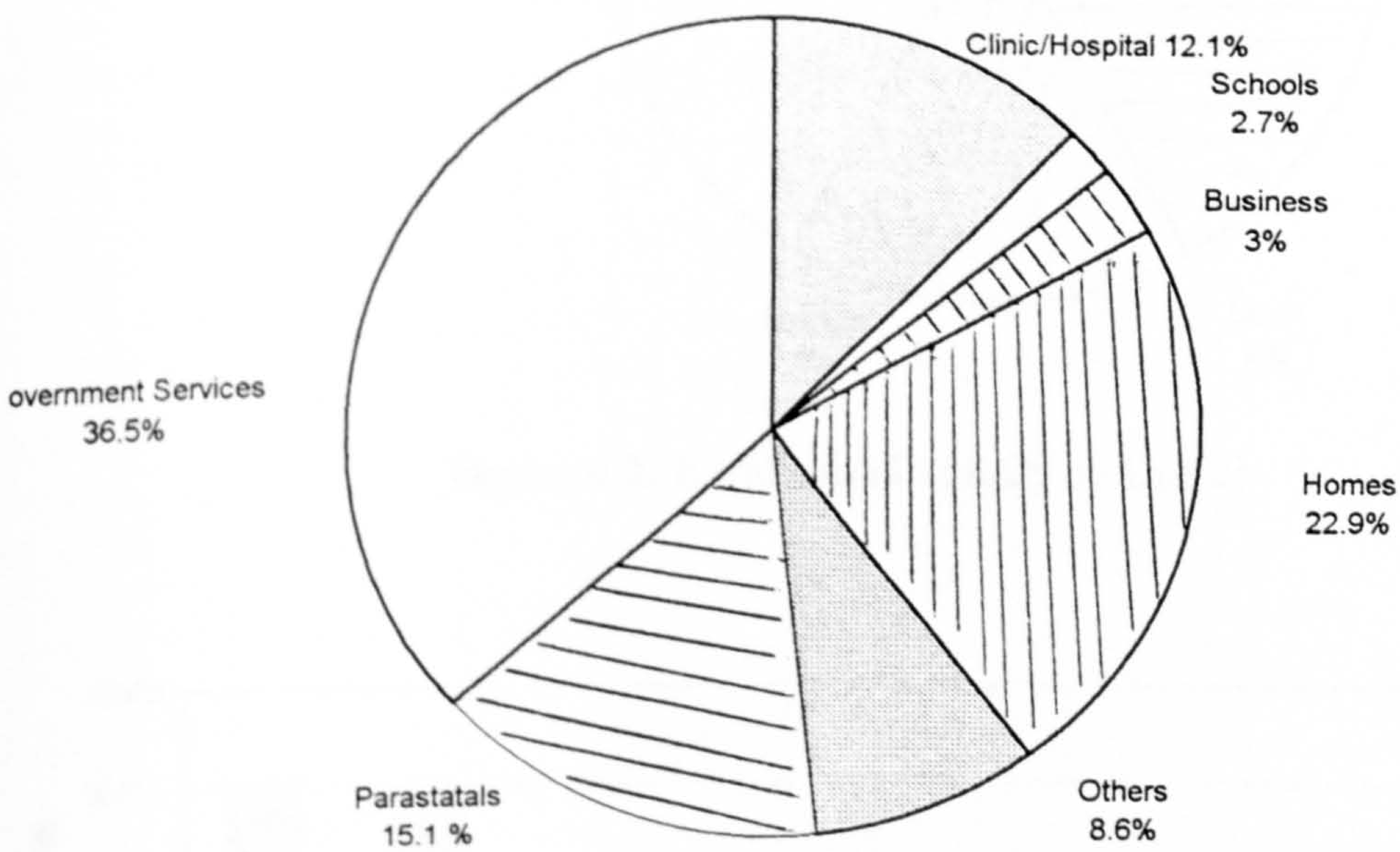


Figure 6.1: Installed Capacity by User

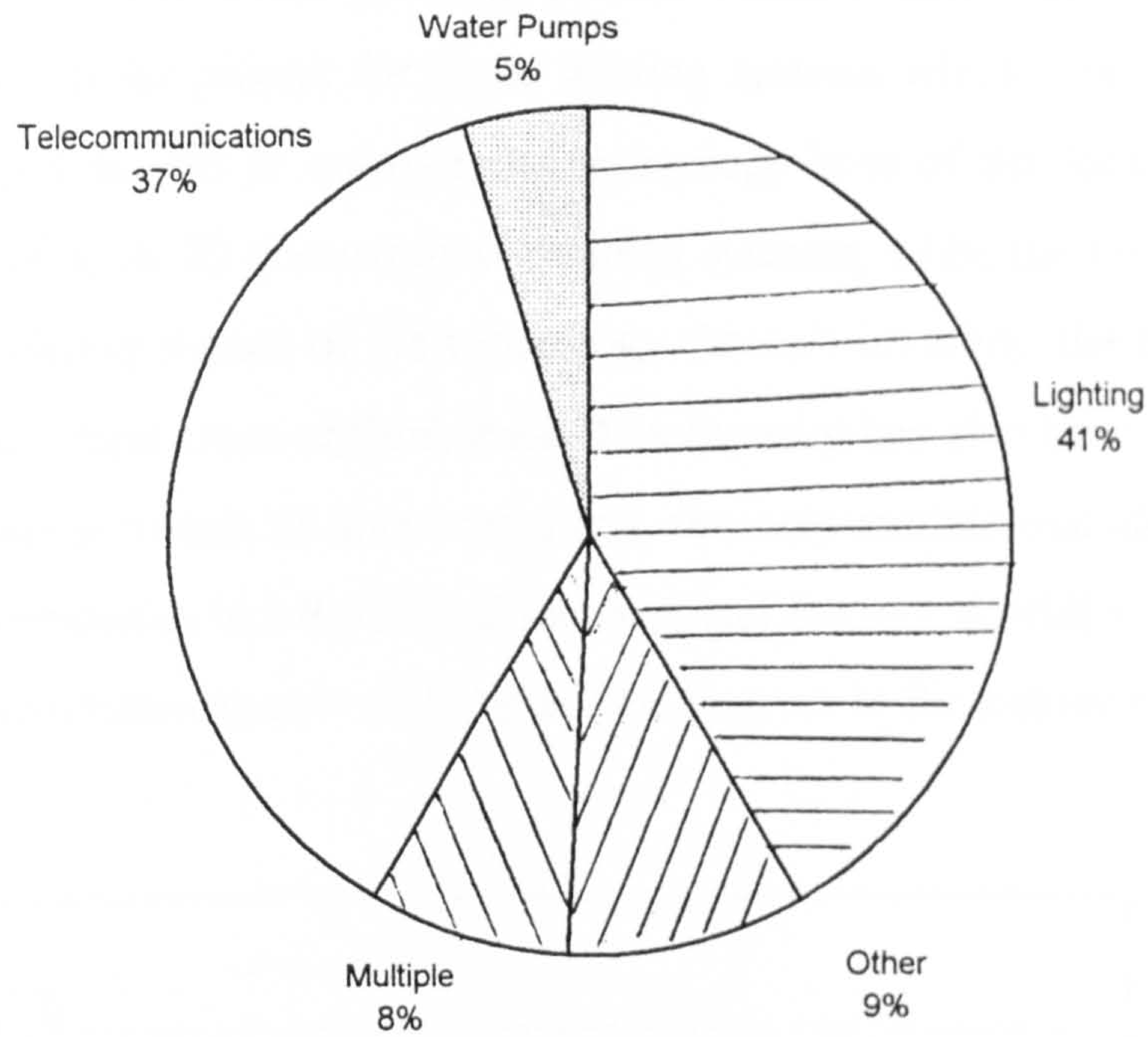


Figure 6.2: Installation Capacity by Use[2]

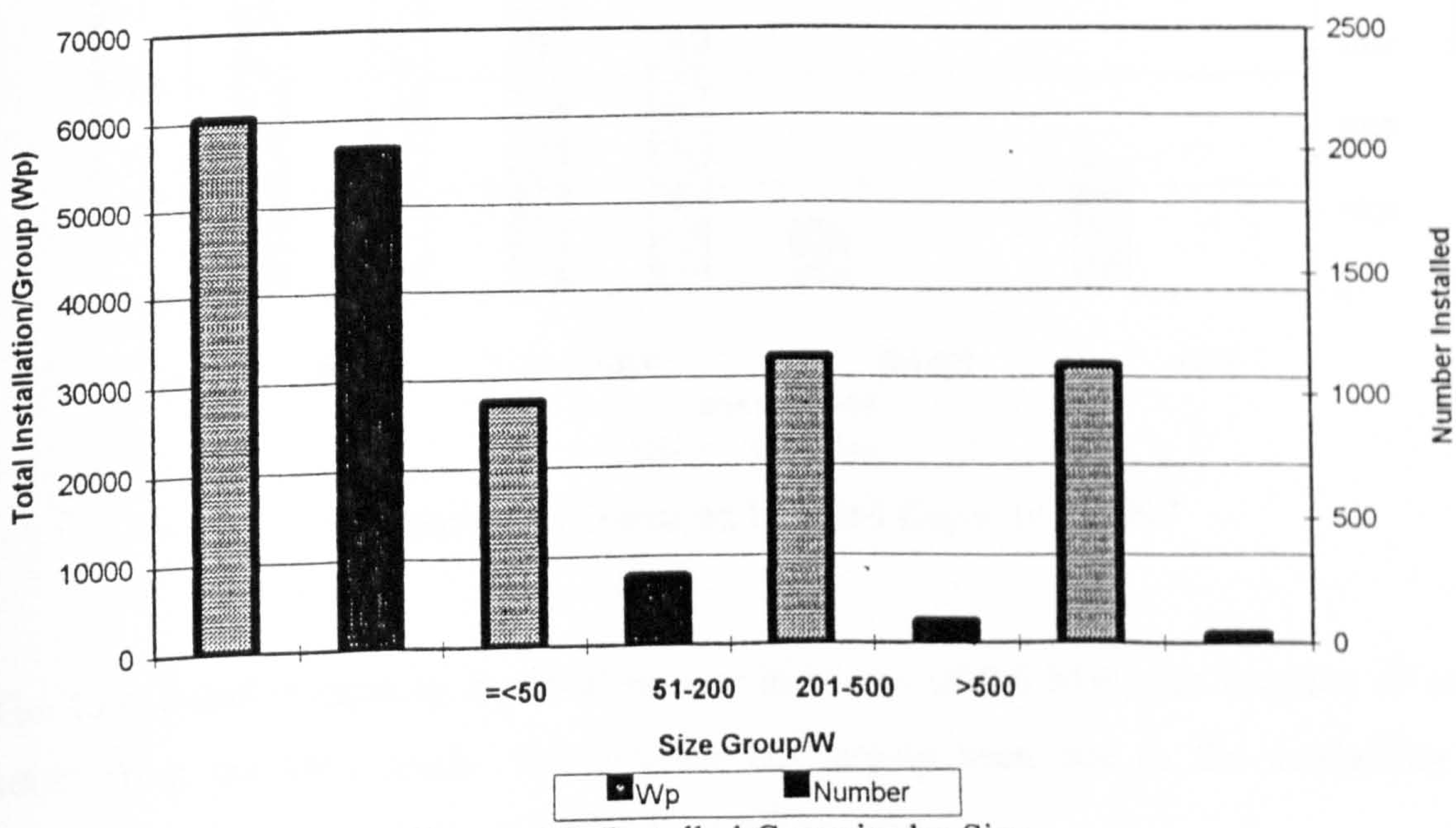


Figure 6.3: Installed Capacity by Size

Since then this capacity has been increased significantly by two major national projects which have accelerated the evolution of the local market to the point where it is ready for various applications of photovoltaic technology to be identified. The first project is the GTZ funded photovoltaic power water pumping project which commenced in 1992[3]. The second was the GEF Solar project for home lighting systems which commenced in 1993[4]. The GTZ project sought to enhance the technology base of the local industry through the installation of up to 20 photovoltaic pumping systems, while the GEF project sought to test various delivery modes of the technology through installing the equivalent of 9,000 45W units in the rural areas of Zimbabwe. The capacity has also been enhanced by the continuing retailing activities of Solarcomm Ltd, the only module manufacturer in the country, and other companies like Sollatek Zimbabwe and Battery World[5]. Through these activities, the approximate capacity of installed PV systems in Zimbabwe by 1997 is as shown in Figure 6.4.

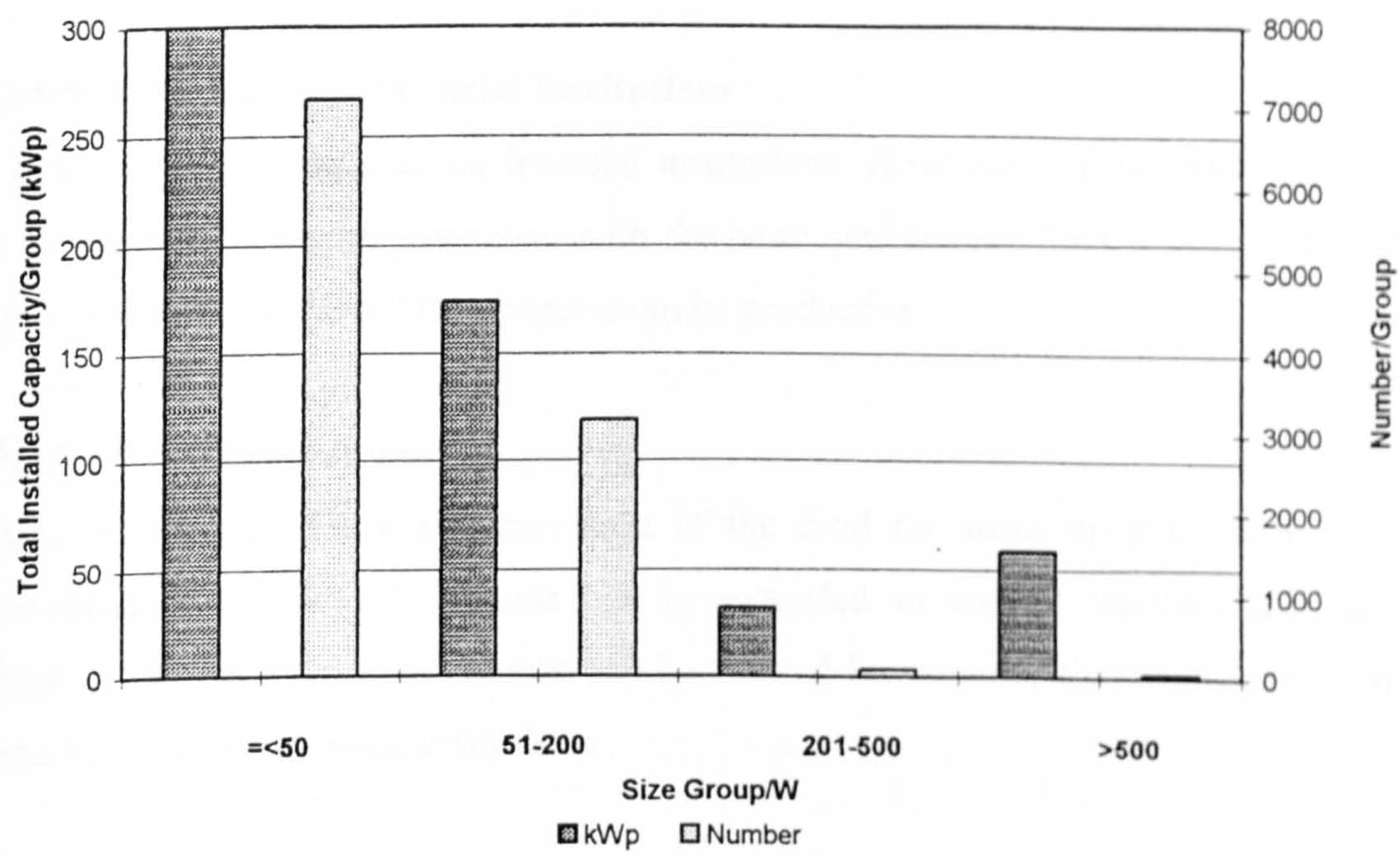


Figure 6.4: Estimated Installed Capacity in 1997

The total installed capacity is therefore now in excess of 0.6 MW_P, an increase of over 300% from the 1991 levels. The increase has largely been due to the availability of favourably financial mechanisms within the GEF project .

6.5 Present Financing of Photovoltaic Power Generation In Zimbabwe

The unavailability of local funds in target markets has been the major drawback for the widespread use of photovoltaics. However, in Zimbabwe strategies for making these funds available have been suggested for a long time. Some of these suggestions follow.

6.5.1 Potential Local Financial Sources

i. Combined Low Interest, Duties and Taxes

The lowering of interest rates and taxes can be applied to renewable energy supplies, while import duties can be waived[6]. Appreciation of the financial needs of rural people has been shown in the GEF project where this type of funding has enabled some rural people in Zimbabwe to take advantage of the PV technology.

ii. Utilising the Existing Financial Institutions

Use can be made of the existing financial institutions. However, the conditions of loan have been too stringent on guarantee, with the basic qualification for the borrower being based on existing income not their capacity to be productive.

iii. Public Work Programme

It has been suggested that a continuation of the food for work programme which is implemented during drought periods can be extended to energy benefits. Instead of working to receive food, a mechanism can be devised for communities to receive energy systems for substantial public work done.

iv. Government Finance for totally local systems

It has also been suggested that floating treasury bills or setting aside a portion of the development levy for the development of renewable energy systems can be another option[6].

6.5.2. The Role of External Sources of Funds

The above local financial sources can then be tapped on a local scale, while at the same time funds from global programmes can be utilised to support the local financial market in the initial stages of its development. This includes participation in a number of renewable energy programmes funded by the World Bank which is an implementing agency for the Global Environmental Facility and the Montreal Protocol (MFMP). The MFMP funds assist developing countries to comply with reducing emissions and production of ozone destroying substances[7]. These energy programmes include

i. The Solar Initiative

This was launched in March 1994, and it aims to accelerate the commercialisation and deployment of renewable energy technologies in developing countries. It was given the capability of utilising GEF sources, and was expected to be the overall coordinating body, assisting with the strategic decisions for renewable energy and promoting accelerated research, development and demonstration of commercial and near commercial technologies. Its strategy was to put high significance on PV projects in developing countries[8].

ii. PV Market Transformation Initiative

This aims to accelerate the commercialisation, market penetration and financial viability of PV technology in developing countries, especially long term prospects of large-scale use of PV. Its appraisal stage which commenced in May 1997. disbursed of US$25million dollars. The minimum leverage of private capital was set at 3:1. This was expected to be enough to promote a bigger market, giving rise to joint ventures, and initiating new finance schemes and promoting public-private partnerships[8].

iii. Energy Sector Management Assistance Programme (ESMAP)

This is supported by the World Bank, the UNDP and other United Nations and bilateral organisations. It identifies and analyses the most serious energy problems in developing countries, and then proposes priority investments and technical assistance projects to address the problems[9].

iv. Financing Energy Services for Small Scale Energy Users (FINESSE)

This was established by the World Bank with the US Department of Energy and the government of the Netherlands in 1989, to promote the market implementation of renewable energy technologies. It aims to identify the potential of renewable energy in various countries, and to assist in utilising them. It assists new industries in the exploitation of resources, generation of wealth within the countries and improve living standards. FINESSE therefore channels low-interest loans and grants through a range of private, utility, non-governmental and commercial lending intermediaries. The first programme was in Asia (Indonesia, Malaysia, The Philippines), the second was in South America, and the third was launched in 1996 in Southern Africa and is administered by the UNDP and SADC[9].

6.5.3. The GEF Solar Project Financial Mechanisms

The result of this line of thought was the ability of Zimbabwe to be in a position where it could benefit from the GEF facility and utilise it to assess local financial mechanisms. The credit scheme to support the GEF solar project became the first functional national financial scheme which catered for renewable energy (specifically PV) ventures in the rural areas. It was set up to achieve the following objectives: i) making credit available to rural households and communities at reasonable interest rates for the acquisition of PV systems; ii) promoting solar electric energy as an alternative source of energy in rural areas so as to avoid environmental pollution from burning candles and paraffin; and iii) supplementing the national electricity grid extension in rural areas where the grid extension was not economically feasible[10].

This was to be achieved by extending credit to the following types of beneficiaries: i)individual subsistence farmers and households; ii) groups of farmers with memberships of 10 to 25 people; iii) registered co-operatives; iv) rural traders and businessmen; v) rural institutions such as schools, clinics and churches; vi) farm compounds on large scale commercial farms; vii) people employed in the urban areas who wanted to install the systems for their relatives in the rural areas; viii) Safaris and wildlife projects

When the GEF project was started the sponsors first approached the commercial banks to manage the revolving fund. The banks refused to promote and manage the fund because they viewed it as non-bankable[11]. This is due to the fact that the merits of renewable energy technology systems had only begun to be understood by financiers. Banks usually cannot afford to service a large number of small clients, whether micro-enterprise lending or renewable energy technologies, because of the high transaction cost per client and low returns to the bank. This is overcome, usually by charging high interests rates and/or bank charges. The banks therefore, tend to have a reduced interest in lending for small scale renewable energy technologies, unless other interested organisations, such as NGOs or credit cooperatives are involved[12]. The latter make lending through these schemes profitable, especially if there is a savings component. The problem was compounded in the GEF project by an interest rate of 15% which was highly subsidised from the normal 35%. The project was also exempted from import duty and surtax. These measures created an apparently artificial demand for the technology resulting in the project being viewed as not sustainable.

It was finally managed by the Agricultural Finance Corporation (AFC). The AFC was best suited for managing the scheme because it had a branch network to reach out to the rural areas and at that time, it was in the process of establishing banking offices at rural business centres and designated growth points. Moreover the availability of PV power to the rural populace was of interest to the AFC because PV provides light energy which can enhance labour productivity of the farming community through additional work in tasks such as grading of tobacco and shelling of groundnuts at night. Lighting for poultry projects also improves the farmers' output. Such a scheme was also likely to improve the farmers' appreciation of PV systems to the extend that they could decide to invest in PV powered pumping systems and refrigeration systems. This would result in the permanent involvement of the corporation in renewable energy projects and in an increase to the individual capacities of the systems it deals with.

Under this scheme loans repayable over three years. These loans were priced as follows:
Insurance Life Cover (for clients of 18 to 65 years) 1.5%

Contribution to Fund	(to make it grow and revolve)	3.5%
Stabilisation Fund	(to cover bad debts)	3.0%
Administration	(by AFC)	7.0%

An initial US$200,000 was provided as grant money to the scheme by the World Bank for the first loans so that local companies who did not have sufficient initial capital could make orders for the photovoltaic equipment. The lack of enough local funds within the local industry was highlighted here, because no physical transfer of money was supposed to have been involved, but this was found to be necessary if the scheme was to get off the ground. The scheme also received funds from sales of capital materials such as panels, loan deposits and receipts, and interest earned on invested money. It involved the clients receiving technical specification and price quotations from solar system retailers . The specifications and quotations were then approved by the project management unit. The client then submitted an application for a loan from the AFC. When the loan was approved the client then paid the AFC a deposit of 15% of the system cost. The AFC then issued a guarantee to the retailer.

This scheme was unique in that the loan terms took into account the background of the clients, the majority of whom are subsistence farmers who could only make payments at the end of their farming year when they had marketed their farm produce. On the other hand civil servants paid monthly through their banks or through salary stop orders operated by the salary service bureau(SSB). The PV system was the end user's form of security. The scheme was also unique in that it ensured that the company providing the system fulfilled its duty of guarantee and after-sale maintenance, because a client's desire to repay depends on whether the system is functioning properly, although the client is still liable for repayment of the loan even if the system is malfunctioning. Since the AFC rather preferred to deal with satisfied clients instead of disgruntled ones, they reserved the right to recommend the right companies to deal with. This in turn forced the system-providing companies to be professional. This safeguarded the interests of the client against unprofessional companies who may have emerged as part of the many providers of the PV systems who participated in the project.

The repayment rate of 85 to 90% was above the normal rate the AFC was used to in its lending. This was indicative of the success of the project in accessing a market. The other success was in improving the technology base. The need to safeguard the interest of the clientele and the marketability of the technology led to the establishment of standards for PV[20] and to a certification process. This forced the retailers to be professional in their participation in the project. The biggest success was however, in the ability to assess various delivery modes. The different modes of delivery of PV systems that were tested were:

i. The Commercial Mode
ii. The Power Utility(ZESA) Mode
iii. The NGO and Donor Mode
iv. The Remittance Community Mode
v. The Money Lender (Community Based Mode)

These modes were assessed for the following features: i) appropriateness of the system designs; ii) functionality and viability of the funding mechanism; iii) social and cultural acceptability and responsible linkages; and iv) environmentally responsive technology utilisation

Features of the commercial mode included: i) a pricing structure for solar systems similar to that for other commercial projects ii) a credit support fund developed along commercial lines. It emerged that the system designs accepted for this mode did not address the low level income groups, and the dissemination mechanism was most effective when it was not rural area clientele oriented.

Features of the Utility based mode included: i) repayment over a long period in the form of a monthly fee which can be a lease, rent or amortised payment; ii) installation and maintenance being the responsibility of the utility; iii) removal of the system in the event of non-payment. PV generated electricity has lower priority than all other ZESA delivery modes. It was found out that the utility had to focus on concentrated consumers in order to fulfil all its roles. The ownership scheme also had the potential to be too complex for individual rural area based consumers. It was observed that the mode would operate most efficiently if a PV mini-grid was utilised. However, a loan was given to ZESA, for installing 500 individual pilot systems for rural homes. This mode was adjudged to be very successful, and it was recommended as the most sustainable mode in terms of long term financing[13]

Features of The NGO/CBO mode include i) servicing community based organisations such as co-operatives and district councils and therefore identifies potential groups of clients first; ii) creating countrywide networks and a wider technology base at grass root level; iii) implementing a pricing structure which includes no tax and reduced transport costs; iv) an integrated approach to rural development which enhances viability; v) providing financial assistance as grants to communities so that they can develop their productive capacity, and use the savings earned from the increased income generated from these economic activities as deposits to obtain loans from the AFC for PV systems; vi) putting together their community savings to obtain larger loans to put up PV systems at schools and clinics and; vii) information dissemination, training facilitators and integrating PV dissemination with fund generating activities. A budget for installing 1000 systems was approved under this model. This mode was adjudged to have flopped[13]. Since this is a UNDP project whose thrust should be on development the fact that such opinion could be given to this mode is indicative of future trends in financing, where more commercial modes will be more successful than the traditional donor based mode.

The Remittance Community mode involved people in formal employment in the urban areas, but with families or relatives staying in the rural areas, being given loans for PV systems to be installed at their homes in the rural areas to pay the 15% deposit. Their rural area based relatives would then pay the instalments. It was decided to link the project to this mode although the project was initially targeted at beneficiaries whose livelihood depended on rural agriculture, because the variable nature of the weather and the low income base did not make the project appear to be bankable.

The Money Lender Community mode included commercial farmers being allowed to put up PV systems for their workers in the farm compounds. The farmer would operate as a money lender by providing the deposit for his workers, while the balance was provided as loan by the AFC. The deposit paid by the farmer was loan to the workers who had to repay it as cash paid on an agreed basis or through additional farm work .

The Savings Groups Mode involved groups such as co-operatives who were encouraged to mobilise savings which would become deposits for the loans from the AFC. It was characterised by participation of people with a history of high financial discipline, who had been able to meet their repayment targets.

The other success of this project was to stimulate the PV retailing industry. The number of retailers before this project was commenced was below 10. However, this number increased to over 30 during the course of the project. Some of these retailers could not meet the stringent loan requirements of local commercial banks. They therefore could not get the working capital required for purchase of PV materials. The AFC therefore provided these companies with financial assistance under the GEF Company Facility at a rate of 35% per annum payable over two years.

The AFC credit scheme was successful in serving the GEF project. However, it clearly showed the need to localise funds and the need to operate from a firm capital base, because the decline of the Zimbabwean dollar at the end of 1997 saw the revolving fund being reduced to a sinking fund, as the invested fund began falling in value with the depreciating local currency. In the end the AFC could not afford to continue lending at the reduced interest rates It is therefore unable to on-lend after the project, although this was supposed to be one of the positive outcomes of participating in the project. The project also managed to highlight the existence of a market whose need for PV power were being obstructed by the lack of finance. There were many potential users who were identified but who could not be assisted under the project because of the development role of the project. They could not be assisted by commercial banks either because of the non-existence of the financial mechanisms to cater for such clients.

6.5.4 Financial Mechanisms and Technology Assessment in The GTZ PV Project

This is an international PV pumping project which is a component of the EPZ, and is co-ordinated as a programme of technical co-operation between the GTZ and the Department of Energy of the Government of Zimbabwe. The project forms part of an international research project in seven developing countries which include Argentina, Brazil, Indonesia, Philippines, Zimbabwe and Tunisia. Its purpose is to demonstrate the capacity of PVP systems for supplying clean water to people in the rural areas reliably. The programme is funded by the German Ministry of Research and Technology.

The aims of the programme included

i. data acquisition over a period of time to assess the practical performance of PVP systems and to facilitate technical and economic comparisons with other water supply options
ii. facilitating the participation of local industry in installing and supplying materials and components for reliably performing systems. This would lead to the establishment of a long term capacity to supply, install and maintain the PVP technology.

The programme sought to achieve the above aims through the following objectives:

i. Considering the short term potential for component substitution within the technical specifications of the fully imported PVP systems
ii. Considering longer term opportunities for localised supply of components or complete systems through the development of local manufacturing capacity and
iii. Considering the scope for local participation in the installation and maintenance of PVP systems and the development of the relevant skills

By 1993 only 4.7% of the 151 kW_p of the installed PV capacity in Zimbabwe was used for PVP systems.[14]. Most of these were supplied to institutional users in terms of bilateral agreements with foreign donor funding. Though not economical the projects offered a valuable service while enabling the development of operating experience. These include 4 large Grundfos PVP systems in the Bulawayo area by Ames Engineering. These were jointly funded by the Evangelical Lutheran Church and Rotary as part of the "Clean Water Project". Stewart & Lloyds acquired 5 SP3A-10 Grundfos 1500W PVP systems at about US$15,000 each. This was funded by Danish aid(DANIDA).

Prior to the GTZ PVP project the most significant PVP pumping installations were as listed in Appendix C.

The greater application of PVP systems in Zimbabwe and the increased local content of components within the systems depends largely on: i) the specific requirements of water in each instance; ii) the availability of water; iii) the availability of a range of PVP systems and; iv)the affordability of these systems to individuals, communities and state departments. Constraint iv. is imposed by the high imported content and high initial cost of PVP systems and the lack of appropriate financing options to allow communities and individuals to buy PVP systems. The potential market for PVP systems in Zimbabwe was approximated at 600 systems with capacities of less than 500m^3/day. This has not been tapped significantly.

Zimbabwean commercial enterprises have in the past been able to obtain foreign exchange through the Open General Import Licenses(OGIL), foreign exchange allowances for trade within the PTA, or through the export retention scheme(ERS) which allowed companies to build up foreign currency allowance based on their exports. The ERS scheme provided a foreign currency allocation of 35% of the export value. The ERS enabled certain companies to accumulate surplus foreign currency allowances which could be traded. This provided wider access to foreign exchange, although at a premium, to companies which would have otherwise been prevented from conducting import related business.

The availability of foreign exchange, for this particular sector, therefore would not have been the primary constraint to the importation of equipment for the project at its inception. Instead the primary contributors to the cost of importing included:

i. the transport and packaging costs

ii. the ruling import duties and surcharges

The latter also included a surcharge of 20% and a duty of 15%. In certain cases further custom charges of up to 10% were levied. The original bilateral agreement between the Zimbabwean government and GTZ made the equipment supplied within the project to be exempt from custom duties, licenses and public charges. This however, did not clearly apply to locally supplied equipment with an imported content

6.6 The Effects of Participating in Global Programmes

It can therefore be concluded that the effect of the international programmes has been to stimulate a significant volume flow of the photovoltaic technology in Zimbabwe. It can be observed from Figure 6.2 and Figure 6.4 that this increment, from about 150kWp to an estimated capacity of over 600kWp, represents an increment of 300% on the existing capacity. The potential of building-integrated photovoltaic systems in the benchmark city as shows in this research clearly shows that the introduction of building-integrated photovoltaic systems in Zimbabwe makes it an effective and strategic niche application which can revolutionise the photovoltaic industry in Zimbabwe.

The estimated potential of PV on exemplar buildings only is sufficient to increase the installed capacity of photovoltaics by a further 200% to 1.5 MW. Extrapolating these results to the building stock shows that the benchmark city on its own can have an installed capacity of up 4MW. This all depends on how such an ambitious strategy is successful in penetrating a traditionally conservative power market. The figure of 4MW cannot have a time period associated with it, because experience with the local market has shown that acceptance of the technology tends to be immediate instead of being gradual, since the need is already there. The interest in the GEF project by clients who were not just from a rural setting, but from a semi-urban setting as well showed that the market is there and is willing to acquire the technology. The latter were however not eligible to benefit from the scheme because it was aimed at developing the rural areas. Therefore, if the technology can be accepted before the end of the decade then this figure can be reached in the time that it takes to establish the proper mechanism for the wide scale use of this technology and for the reliability of the industry.

The growth of a country's commercial sector and therefore its power needs usually goes hand in hand with the economic growth. For a developing country like Zimbabwe a stabilised growth rate of 8% can be anticipated at the end of the century. An equal growth in the photovoltaic market implies that the market will have grown to about 10MW at the beginning of the second decade of the next century. This will definitely have implications on the manufacturing capability available, creating a scenario where local manufacture of

PV in Zimbabwe has to be considered carefully as a long term plan. There is much scope for being optimistic about the manufacturing capability of photovoltaics in Zimbabwe. Only as recently as the late 1980s Zimbabwe was said to have the most developed economy in independent Africa, outside South Africa[17]. Its economy is also diverse compromising of a number of strong sectors such as mining, agricultural, manufacturing and processing with essential activities such as chemical processing which are required if local PV manufacture is to be successful. The sole module assembling plant in Zimbabwe has shown that projects of this nature are sustainable, and that there is a large amount of untapped potential in this area. This existing national infrastructure can easily facilitate the setting up of a manufacturing plant.

Clearly, increase in demand has also increased the capital base from which the technology operates, with a total of up to 30 retailing companies coming into being within the life of the GEF project alone, and the SEIAZ becoming revered in the energy industry. They have also led to the establishment of various standards[20] for the industry through the activities of the PMU, SEIAZ and the Standard Association of Zimbabwe. One of the outcome of this was the identification of the importance of jump starting the market and industry so that the technology can be sustainable. However, the jump-starting was meant for a development purpose which did not cater for all sectors of the economy. Consequently, the sustainability was limited and in the end some observers began seeing the revolving fund as a sinking fund[13]. The onus is on the local players in Zimbabwe to establish a jump-starting mode which results in more sustainable revolving funds within the market and industry. This has to be more ambitious than a rural area based developmental programme. A building-integrated photovoltaic approach provides this possibility and the considerations made in this research make the following recommendations necessary.

6.7 Recommendations

It is recommended that the work done here be extended in three directions as follows:

6.7.1 Establishing a capacity-building facility for building-integrated photovoltaics in Zimbabwe.

The development of a capacity building facility for the utilisation of photovoltaics in the form of building integrated photovoltaic systems in Zimbabwe should be done, preferably at a scientific research centre with a capability of dealing with built environment and energy matters. This facility should be fully equipped with facilities for information transfer, energy auditing, computer aided design software as well as software development. The facility should involve the acquisition of extensive preliminary information on photovoltaics and the building industry in Zimbabwe. The facility should be perform the following duties

- Identifying the related projects that have been done already and that are ongoing in Zimbabwe which can be used to consolidate the sustainability of the facility.
- Establishing a link between the existing and anticipated energy policies and the resulting policy changes that may be required to accommodate the building-integrated technology.
- Establishing a link between the existing and anticipated building by-laws and the resulting changes that may be required to accommodate the building integrated technology.
- Identifying the personnel from various disciplines and industrial sectors that will eventually be involved in project for promoting building integrated project. It is anticipated that these will be electrical engineering, energy technology, building technology, architects and mechanical engineering personnel.
- Identifying external centres of expertise which can assist in technology transfer matters and who can participate in the induction of the personnel above into photovoltaics and PV cladding of buildings.
- Carrying out detailed topographical studies of the commercial buildings in major cities in Zimbabwe utilising analytical tools which will lead to an appropriate database for future full scale computerised energy analyses.
- Extensive energy auditing of the commercial buildings
- Detailed computer simulation of the energy consumed by each load type within the building stock.
- Correlation of the actual measured energy consumption with the results of the simulations to validate the capacity of the simulation software as an estimation tool.

- Detailed analysis of the potential of the solar energy resource for utilisation with the building integrated photovoltaic technology.
- Development of in-house computer software which can be used to establish various algorithms to deal with the various energy utilisation paradigms identified during the course of the simulations and which can allow photovoltaic system implementing strategies relevant to the local area to be assessed.
- Stimulating the interest of the local energy, building and financial communities by holding regular seminars and workshops.
- Liasing with the power utility(s) and present and future independent power producers
- Formulating strategies to enable related projects involving members of the appropriate industries to be undertaken, so that the potential of a commercial mode of implementation of the technology can be assessed from an early stage.
- Assessment of the local industry to gauge their capacity to provide the required sustainable technology base for a technology which is meant to promote sustainable energy generation.
- Identifying potential local financiers for a future demonstration project.
- Sourcing funds for and implementing a demonstration project.
- Documentation of the results obtained and of recommendations identified from an actual system.
- Identifying opportunities for more similar projects.

6.7.2 Coordinating A Strategy for Local Manufacture

It is recommended that investment in future local PV manufacture be made top priority. This should begin with the training of personnel in related disciplines and encouraging the growth of industries which will play supportive roles to the local manufacturing plant(s). A significant part of the developing world population who can afford the photovoltaic technology at today's prices are being wrongly labelled as part of the rural poor. If the photovoltaic industry could access these people it is widely believed that the existing global manufacturing capacity will not be able to cater for them. It therefore makes sense to have locally produced PV so that its availability is not limited by the priority status given to country by external manufacturers which may depended on criteria which the country cannot meet. Moreover, experience with foreign exchange mechanisms in developing countries show that the sustainability of local funding is limited if the photovoltaic technology is imported.

6.7.3 Enforcing A Sustainable and Equitable-Development Energy Policy

The existing anomalies between the shortage of energy and the apparent misuse of it in commercial buildings through sometimes unnecessary air-conditioning systems and lighting loads should be capitalised on by either charging a 'green' tax on commercial buildings owners who have such buildings so that the money can be used for photovoltaics and other renewable energy systems. Alternatively, since it is obvious that such buildings will continue to be built, the owners should be forced to adopt photovoltaics as one of their energy sources. The two recommendations may seem harsh but are more likely to be found more acceptable against a background of potential blackouts and escalating energy bills. Lastly, since effective administration centres tend to be located where there is electricity, the priorities should be changed such that such centres are established anywhere where they are needed regardless of their remoteness from the grid. The centres should then be provided with all the amenities of a central business district and their power supply should come entirely from photovoltaic systems. This would result in more equitable national development.

6.8 Conclusion

This study sought to establish the potential of the building-integrated photovoltaic technology on commercial buildings in Zimbabwe and to formulate possible strategies for introducing the technology in a way that it will become a niche application which will redefine energy generation in Zimbabwe. This was achieved by considering factors that affect the feasibility of this technology on actual buildings in the building stock of a benchmark city in Zimbabwe. It was concluded that the building stock had huge potential for integrating this technology because of the trend in the architecture of its buildings, the availability of the solar energy resource, the economic capability and awareness to environmental issues of the building owners, and most importantly the constraint being imposed by problems associated with relying solely on conventional sources of electricity whose supply is being outstripped by demand. The was further helped by the fact that all the features that are being exploited in the developed world to integrate PV on commercial buildings such as rainscreen wall cladding, sunshading systems and state-of-the-art curtain walling and other aesthetic considerations are present on buildings in Zimbabwe. The sunshading system in particular was found to offer the best opportunity to integrate PV on most buildings.

The simulations done in this study identified one category of recent buildings in which the integration of photovoltaics was not only possible technically, but was economically viable if photovoltaics was considered in the design stages of the building and even after that stage. This category includes buildings without full mechanical air-conditioning, but which are passively ventilated and which have energy conserving features. Such buildings have lower demands than conventional commercial buildings and they have surfaces which allow for the easier integration of photovoltaic modules without much alteration to the building envelope. It was concluded that this potential needs to be demonstrated by a practical example so that building can be propelled into becoming a niche application. Therefore this work will be extended in Zimbabwe with the intention of setting up a demonstration project on one of the building investigated. It was also concluded that targeting air-conditioning loads in the buildings in all the categories in general enhanced the potential of building-integrated photovoltaics because of the better correlation between the demand and the supply and because of the possibility of the whole load being met by the supply.

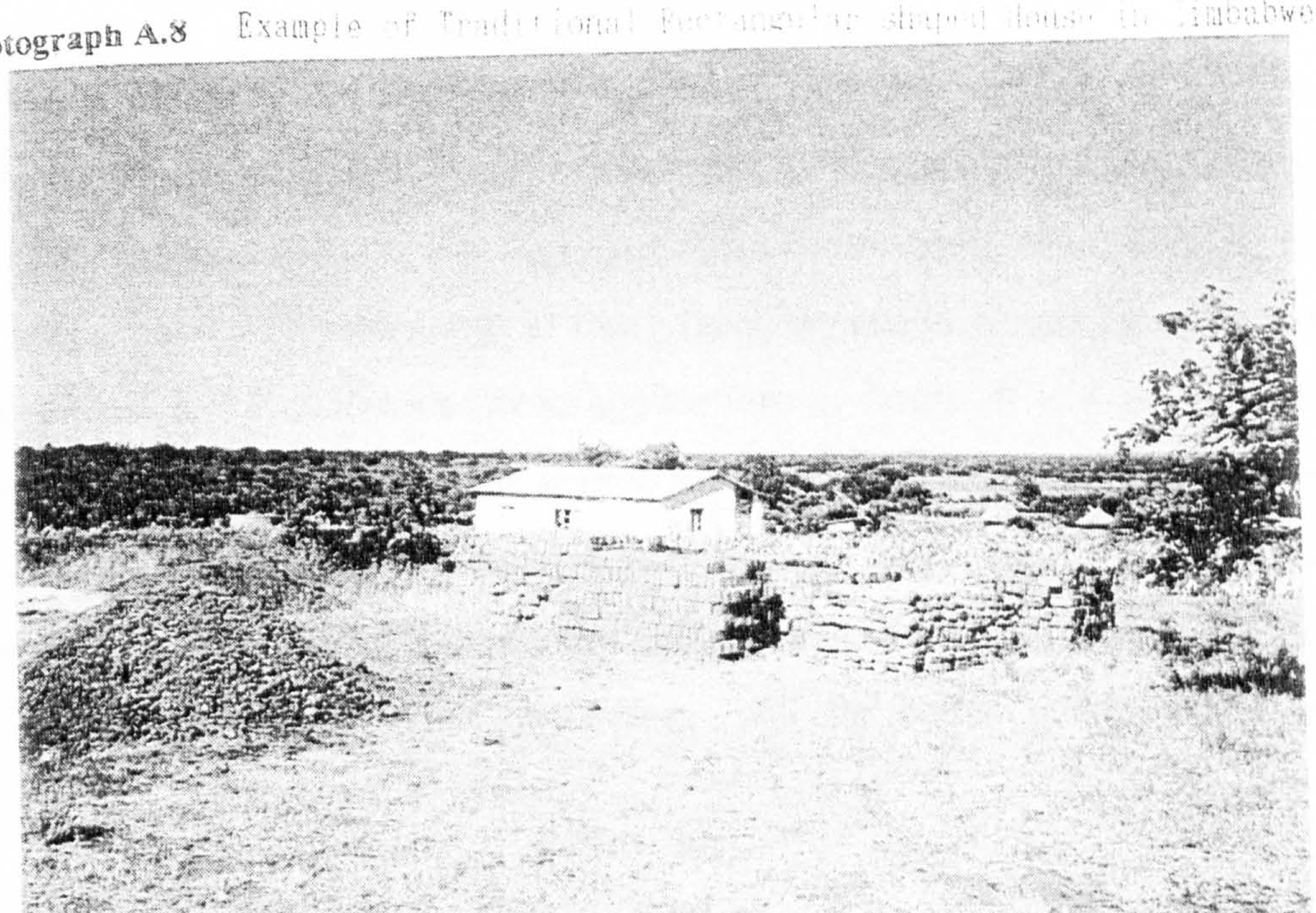
The socio-economic issues considered in this study, brought a conclusion that building-integrated photovoltaics is the most practical and sole energy generating technology which can solve the problems associated with no capital being available for an energy generating technology in such a way that all strata of the economy can benefit from it. It was also concluded that this technology is a natural extension of the evolution of the national energy policy of Zimbabwe of providing energy to its populace in an environmentally friendly manner. This was confirmed by assessing the national activities on renewable energies which showed that the hurdle of a national energy policy which is not favourable to photovoltaics and renewable energies in general has long been overcome in Zimbabwe. It was also concluded that the experiences gained through global renewable energy programmes established a firm base on which ambitious energy programmes involving photovoltaics can now be undertaken. This, together with the need to reverse the trend whereby the development of the country is tied to conventional energy sources and their associated spiralling debt justifies the need to seriously invest in the building-integrated technology.

It was also observed that the development in the energy needs in rural areas has an impact on the built environment . The chronology of dwellings in the rural areas as illustrated by Photograph A.7 to A.9 shows that their architecture is greatly influenced by the source of energy utilised within them. The traditional thatched hut best suited the centrally located wood fire which served both purposes of cooking, lighting and heating. As candles and kerosene lamps became dominant as light sources the thatched hut was superseded by the thatched rectangular brick house as the preferred communal dwelling. This latter is becoming increasing superseded by the rectangular brick house with a sheet metal or asbestos roof as more accessories powered by batteries and other sources become available. The photovoltaic technology will therefore have an impact on the building technology in these dwellings, especially as the mounting options make the effect of the module on the building skin more significant as the systems become larger with time. It was therefore concluded that it is necessary to have the aspects of building-integrated photovoltaics well understood before the rural utilisation of PV reaches this stage by using PV on commercial buildings.

It was also concluded that for the photovoltaic systems to be applied on a large scale in areas where the grid does not reach, the problem of a more suitable energy storage had to be addressed. Batteries have been found to be less reliable because of their depth of discharge losses, limits of the state-of-charge, their differential behaviour in response to temperature effects, and their working regime which does not give the same performance and the same lifetime with PV as with say automobiles[18]. While research into batteries

Photograph A.7 Example of Traditional Circular-shaped House in Zimbabwe

Photograph A.8 Example of Traditional Rectangular-shaped House in Zimbabwe



Photograph A.9

which are more suitable for PV is ongoing there is a need to look at other alternatives. These may include ice-storage which would be more suitable where office-building air-conditioning is to be used [19], and which will also assist in improving the correlation between the PV power supply which is dependent on the variable nature of the solar resource, with the demand which is dependent on the variable nature for the energy-user profile. This lack of correlation has been the main handicap used to dismiss PV as a large scale energy generating source.

In this work the technical aspect of many environmental effects on the PV system have not been treated in depth. This is because this work sought to establish the potential of methodologies suitable for the target market which will then be treated to such depth. In some cases, as in temperature effects on the modules, it was assumed that the PV sunscreen system would allow the heat generated by the panel to be effectively removed by natural ventilation so that no adverse heat build-up could either affect the internal environment of the building or the performance of the modules. However, it was realised that other methods of integration are possible and methods of optimally integrating PV with these method have to be investigated. This can be in the form of using a PV curtain-wall whereby the heat generated by the PV modules is allowed to rise and instead of being recycled to heat the building as proposed for cooler climates in the Joule project PV-HYBRID-PAS[18], the heated air is used to ventilate the building through the chimney effect as proposed by Abbro and Pitts[21].

It can be concluded that this research has shown that photovoltaics have evolved into a truly modular technology which can be integrated into various engineering disciplines with the building engineering being the most significant future application. Building-integration has finally given the PV technology as much flexibility and importance as microelectronics. Consequently, it will find widespread applications in future. It was therefore concluded that a potential market has to keep in step with the state-of-the-art of PV in order to be able to identify the applications that will best serve its needs. Building-integrated PV also allows for the gradual integration of new developments in the technology. For instance, a well established PV sunscreen technology will be better prepared for integrating concentrator technology if it becomes feasible to use it on building. Already ways of using this technology on buildings[22] are being investigated.

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Appendix A
Weather Data

The Construction of A TMY File

Solar radiation, temperature and wind speed affects the performance of a PV system. The solar radiation for the benchmark city was available on an hourly basis in hard copy. Temperature data was only available on a 3 hour basis. The monthly averages of each month for both solar radiation, dry bulb temperature, wind speed and sunshine hours are shown for 10 years of data in the following tables:

SOLAR RADIATION (MJ/DAY)												
ANN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
1985-86	17.7	19.9	20.5	22.1	21.0	18.3	19.9	19.7	21.0	18.2	19.0	18.7
1986-87	18.6	21.2	21.6	20.7	22.2	20.2	22.4	22.0	21.9	22.3	18.9	18.3
1987-88	17.2	19.9	21.5	24.3	24.8	19.1	24.1	20.9	19.6	19.9	16.9	20.5
1988-89	17.5	21.3	23.1	22.3	22.7	19.8	19.2	14.2	18.9	19.7	20.3	19.0
1989-90	15.8	20.1	20.8	21.5	21.8	21.6	18.6	19.3	21.3	18.8	18.9	19.5
1990-91	17.6	20.0	21.7	22.6	22.4	20.1	22.0	19.7	19.8	20.0	17.8	18.6
1991-92	16.6	20.6	21.4	22.6	20.4	21.2	22.0	23.8	18.7	19.7	18.5	17.4
1992-93	16.8	19.5	22.2	22.1	22.6	16.9	19.6	18.2	19.2	18.2	18.5	18.4
1993-94	17.8	20.3	22.1	23.7	22.3	20.6	20.6	17.1	19.8	19.0	16.5	18.2
1994-95	17.5	17.6	20.4	22.0	22.2	23.8	20.9	20.4	22.4	20.0	18.3	16.5

DRYBULB TEMP. (DEG. C)												
ANN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
1985-86	13.5	18.5	19.9	20.0	19.7	19.6	19.6	19.6	18.1	15.1	12.2	17.8
1986-87	12.4	15.1	18.1	20.3	21.2	20.3	20.8	17.8	16.5	12.2	17.5	17.6
1987-88	12.2	15.7	19.6	20.0	22.7	21.0	21.3	20.2	19.7	19.3	15.3	
1988-89	13.1	15.0	18.2	20.4	19.7	20.0	20.2	19.0	19.3	17.5	15.3	13.4
1989-90	13.0	15.0	17.5	19.4	20.8	20.6	20.0	19.2	19.5	18.4	15.9	14.1
1990-91	13.9	14.7	17.1	21.0	21.0	20.9	20.7	20.4	19.9	17.8	15.8	13.4
1991-92	13.0	15.4	19.6	20.8	20.6	20.3	21.6	22.1	20.9	19.1	16.1	13.4
1992-93	12.8	14.7	19.1	22.2	21.2	20.1	19.8	19.3	18.7	16.4	13.0	
1993-94	13.5	14.8	18.1	21.2	20.4	20.9	20.1		14.7	13.0		
1994-95	12.0	15.1	18.8	19.2	22.8	21.0						

			SUNSHINE DURATION (HRS)									
ANN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
1985-86	8.9	9.5	8.7	9.3	7.4	4.3	5.6	6.8	7.9	6.7	9.1	9.3
1986-87	9.6	10.1	9.7	8.0	8.6	6.8	8.0	9.3	8.5	10.3	8.7	9.8
1987-88	10.4	8.4	9.3	9.5	9.2	5.5	8.5	6.4	6.6	7.9	7.8	8.8
1988-89	9.3	10.1	10.5	8.9	8.8	6.5	6.6	3.0	6.9	8.5	9.7	8.1
1989-90	8.9	9.5	9.1	8.4	8.3	8.3	5.3	6.6	8.3	8.0	8.2	7.5
1990-91	9.9	9.3	9.7	9.9	9.0	6.9	8.0	7.1	7.3	9.0	8.5	9.7
1991-92	9.4	9.6	9.9	9.3	7.6	9.0	11.0	7.1	8.7	9.3	9.0	
1992-93	7.6	9.6	10.3	10.0	8.8	4.7	6.5	7.7	7.6	10.1	9.3	
1993-94	7.6	9.2	9.6	10.6	7.3	7.8	6.0	7.8	9.8	9.2	9.8	9.3
1994-95	9.7	9.1	10.5	8.7	9.9							

		CLOUD AMOUNT (OKTAS)											
ANN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR		MAY	JUN
1985-86	2.2	1.6	2.3	2.5	4.4	6.8	6.1	5.6	4.8	4.8	2.0	1.4	3.7
1986-87	1.3	.9	1.6	4.5	3.9	5.0	5.2	4.4	3.6	1.7	2.4	1.3	3.0
1987-88	.6	1.7	1.8	2.7	3.0	6.5	4.9	5.8	5.1	4.5	3.1	2.4	3.5
1988-89	1.7	.9	1.0	2.7	3.8	5.2	5.6	7.0	4.7	3.6	1.5	2.4	3.3
1989-90	1.8	1.7	1.5	2.7	4.2	5.2	6.5	5.3	3.2	4.1	3.3	3.0	3.5
1990-91	.9	2.1	1.5	1.9	3.1	4.9	5.3	5.6	4.7	2.7	2.6	1.6	3.1
1991-92	1.5	3.4	2.5	4.4	4.7	4.0	2.9	4.8	3.2	2.3	2.1		
1992-93	1.0	1.4		2.0	6.1	6.0	6.1	4.8	4.2	2.3	1.8		
1993-94	3.9	5.1	1.6	4.8	5.2	5.9	5.3	3.2	2.2	2.0	1.6		
1994-95	1.4	1.7	.8	3.2									

There was a need to select a typical meteorological year based on the available data. There are 2 approaches to develop such a file. One is the use of mathematical models using time series techniques to fit the data with the stochastic model. The second approach uses the empirical method. By dividing the year into calendar months, typical meteorological months (TMMs) can be chosen for by statistical methods from many years of data. Twelve TMMs can then form a TMY. To choose the candidate months for the 5 years the deviations of the short term mean daily values for global radiation in each month were examined with respect to the long term values, using the Root Mean Square Difference (RMSD). RMSD is defined by

$$\mathrm{RMSD} = \left[\sum_{i=1}^{N} \frac{\left(x_{li} - \overline{x}_s\right)^2}{N} \right]^{0.5}$$

Where l and s denote long-term and short term mean daily distribution respectively, and N is the number of observation. The long term mean daily are as follows

	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
	18.3	20.3	21.8	21.9	22	20	21	20.2	20.1	19.6	19.8	17.2

The following RMSDs were obtained

ANN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
1990-91	0.3	0.3	**0.10**	0.7	0.4	**0.1**	1	**0.5**	**0.3**	0.4	2	0.4
1991-92	0.9	0.3	0.40	0.7	1.6	1.2	1	3.6	1.4	**0.1**	1.3	0.6
1992-93	0.1	0.8	0.40	0.2	0.6	3.1	1.4	2	0.9	1.4	1.3	0.4
1993-94	**0.1**	0	0.30	3.7	**0.2**	1.9	2	0.9	1.7	1.4	**0.9**	**0**
1994	1.8	2.7	1.40	**0.2**	0.7	0.2						

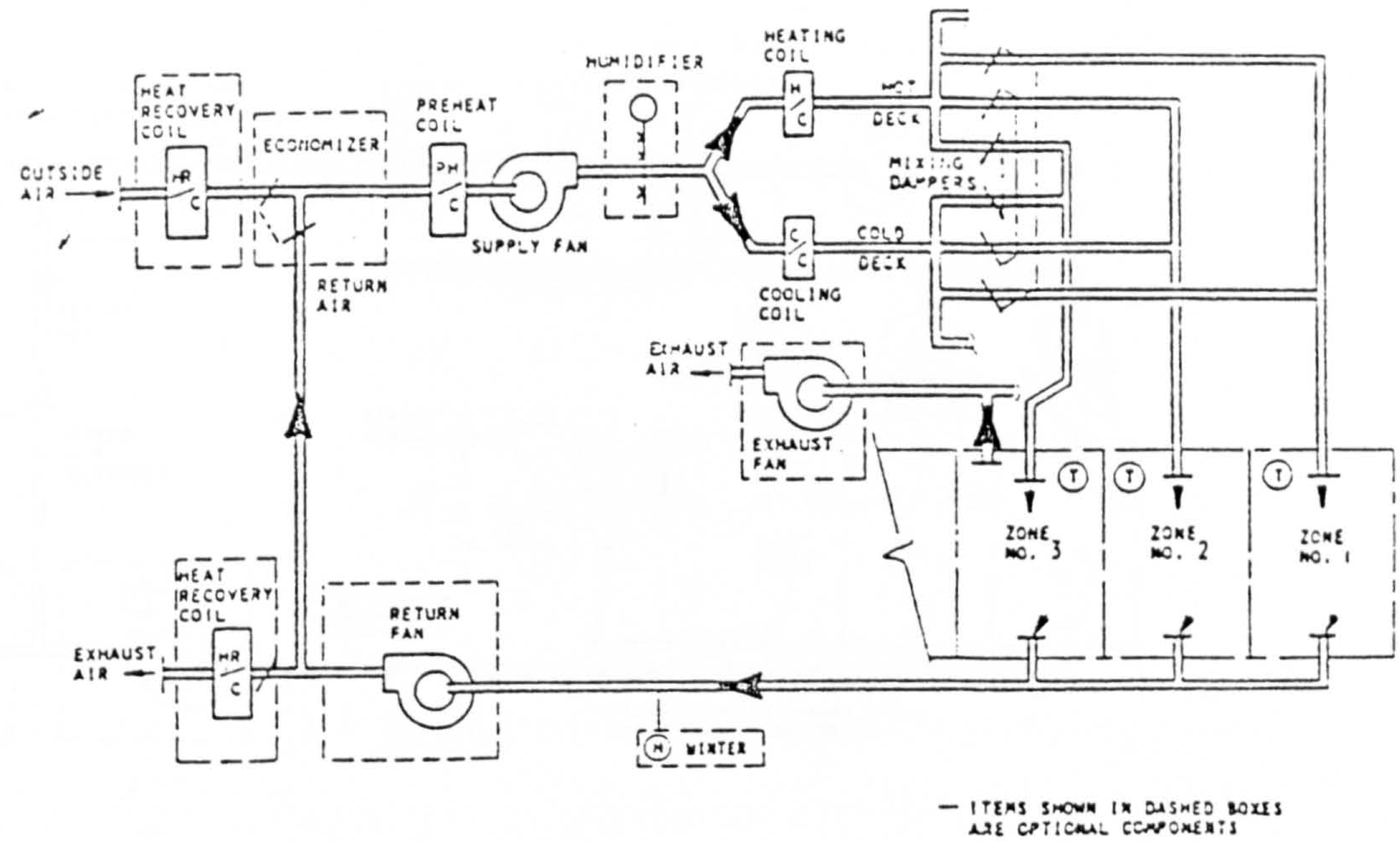
It follows that the TMY for this limited period would have

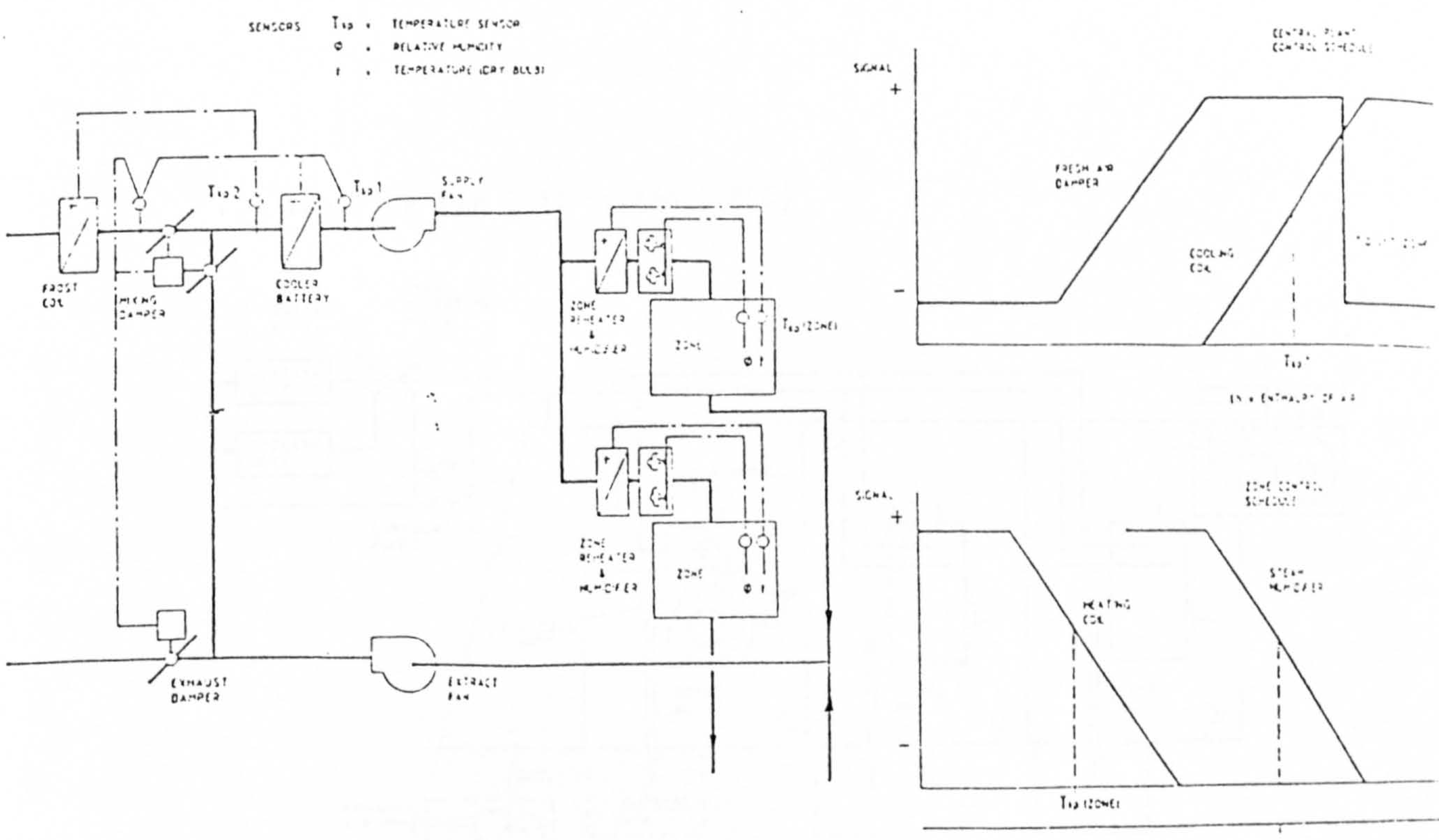
January 1992, February 1991, March 1991, April 1992, May 1994, June 1994, July 1993, August 1993, September 1990, October 1994, November 1993, December 1990.

A typical meteorological day is then chosen by looking at the average value for each hour. The best day for the month which closely follows the pattern of values for the each hour is then chosen as the TMD. The respect TMDs for the hottest and coldest months of October AND July were October the 24 and 6 July. This was a pragmatic approach given the lack of hourly data in the five years. In the commercial energy simulations where a continuous flow between solar energy and temperature were necessary the full hourly data file of 1994 was used.

Appendix B
Air-Conditioning System Schematics

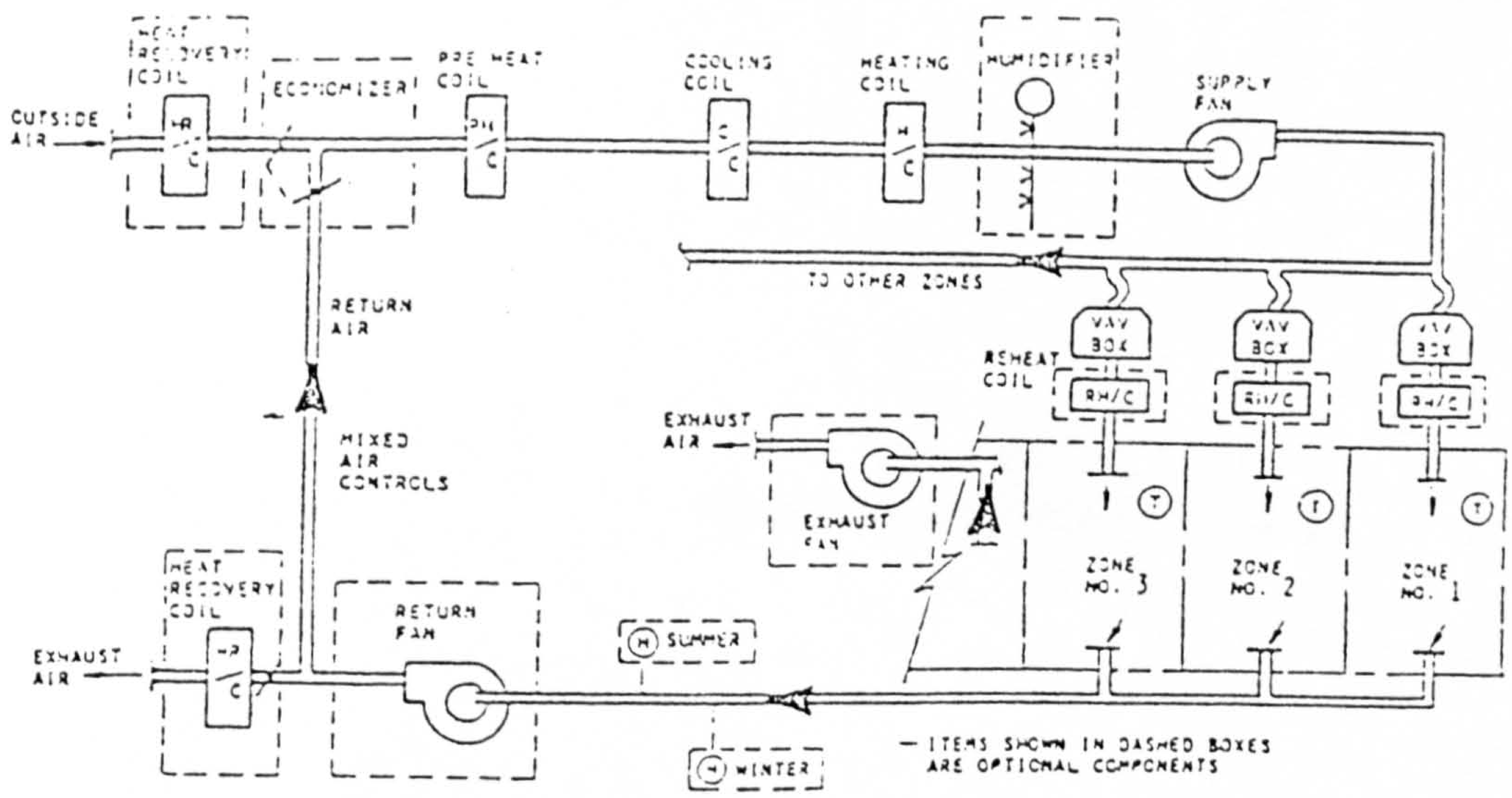
c. Multizone Fan System (MZS)



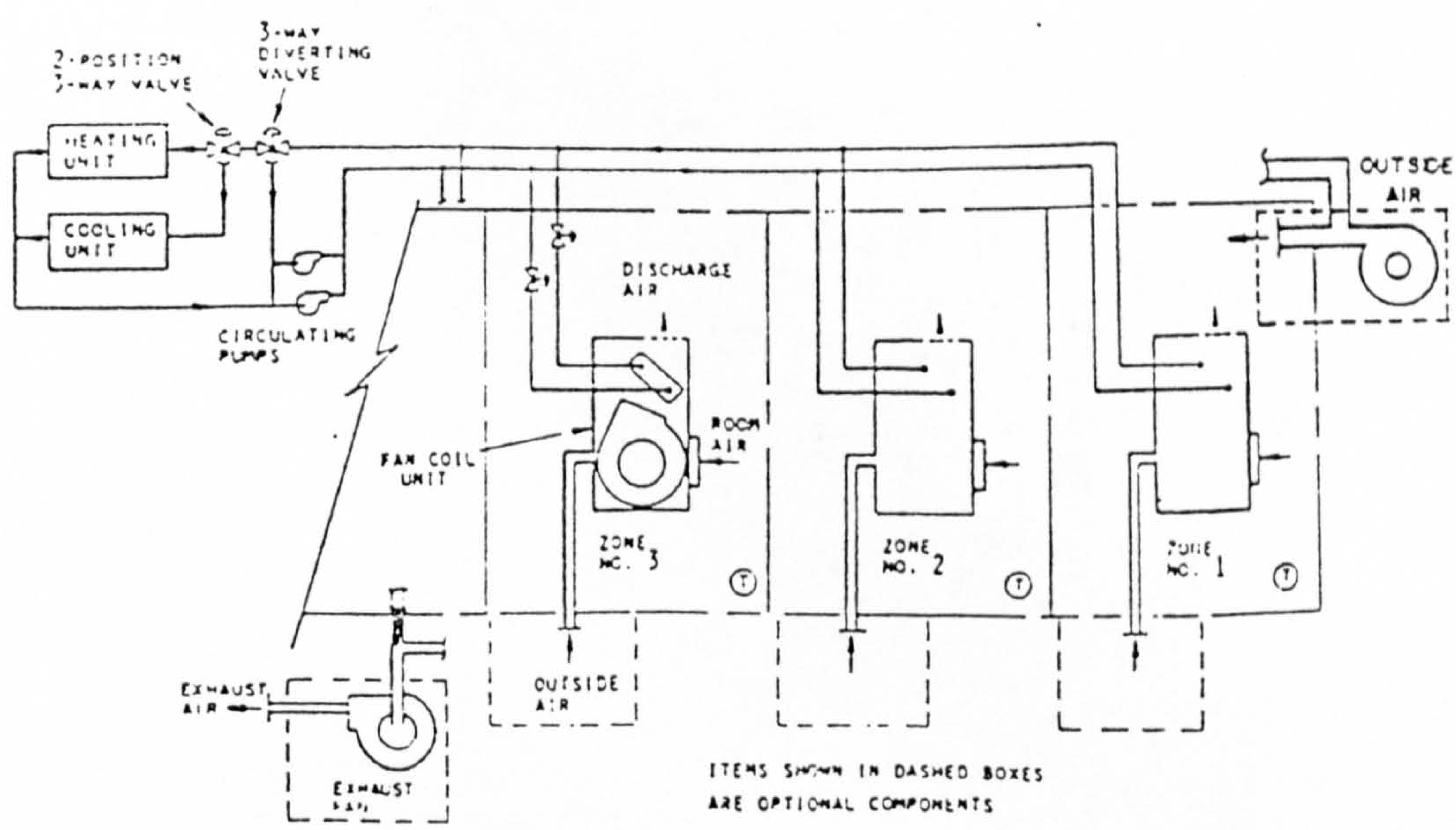


(Constant Volume System)

m. Variable-Volume Fan System w/Optional Reheat (VAVS)



i. Two-Pipe Fan Coil System (TPFC)



Appendix C
Existing Cladding Systems

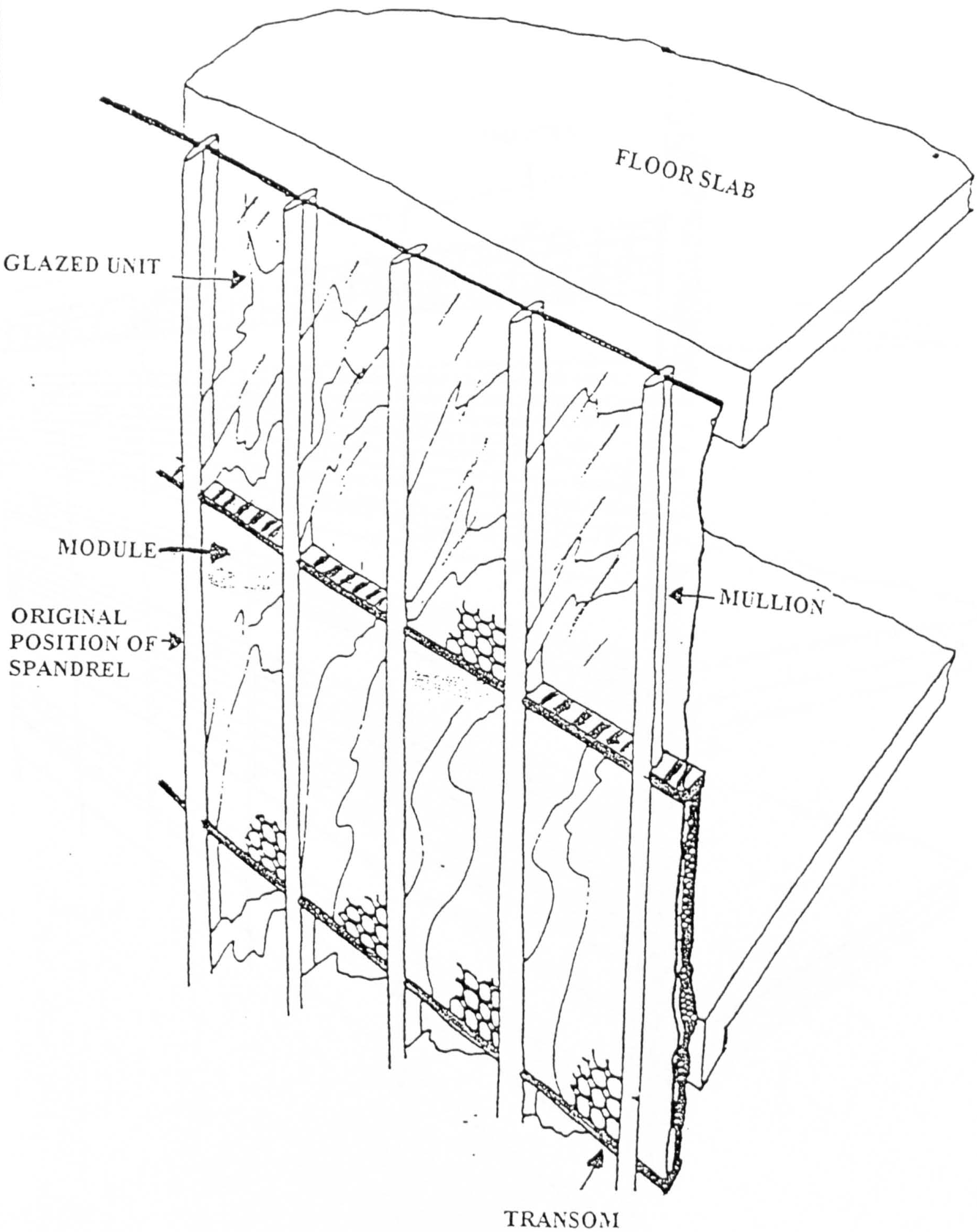


Figure C.1

Mullion/transom stick system

Possible configuration of PV modules

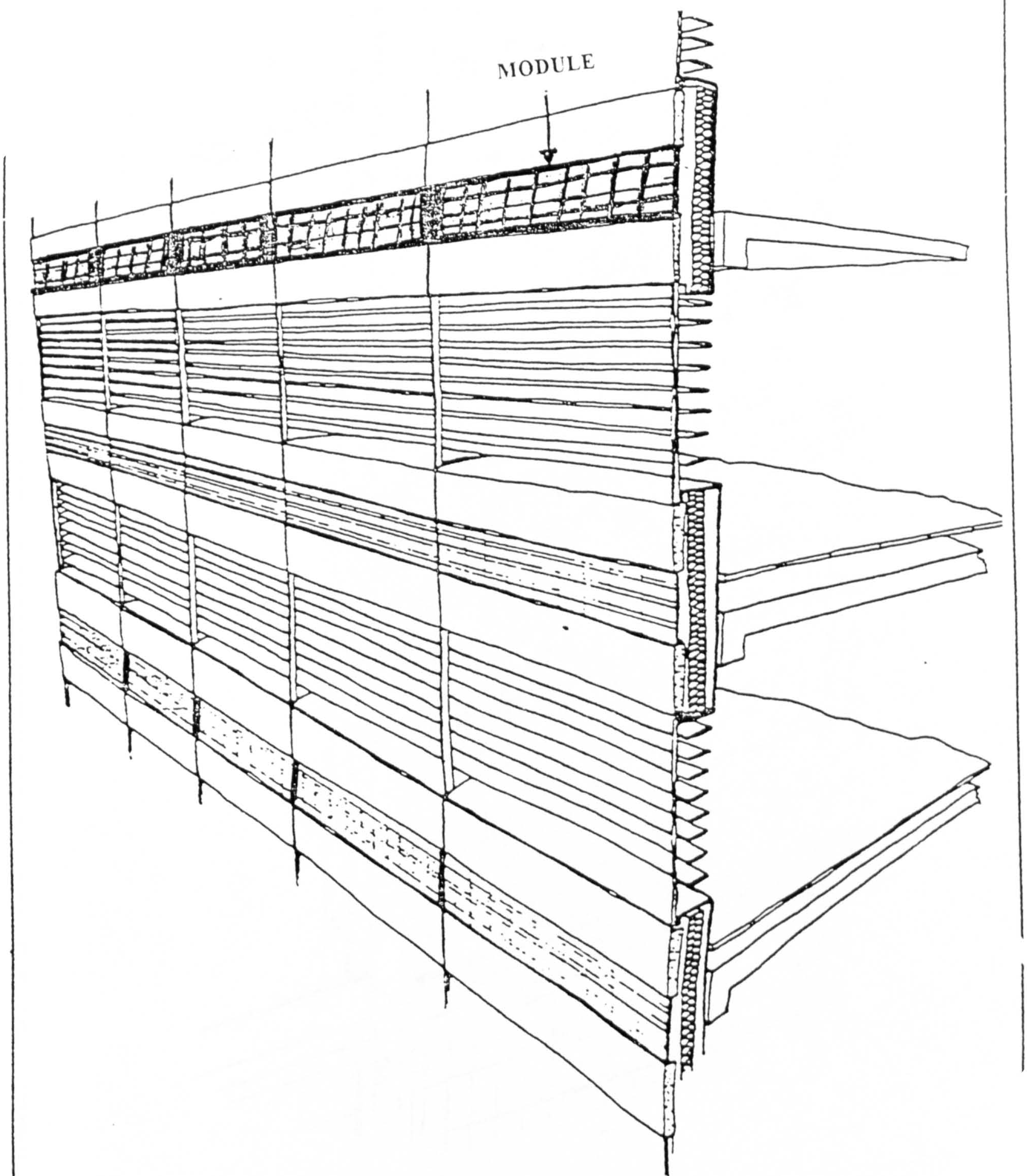


Figure C.2

PV modules integrated into panel system

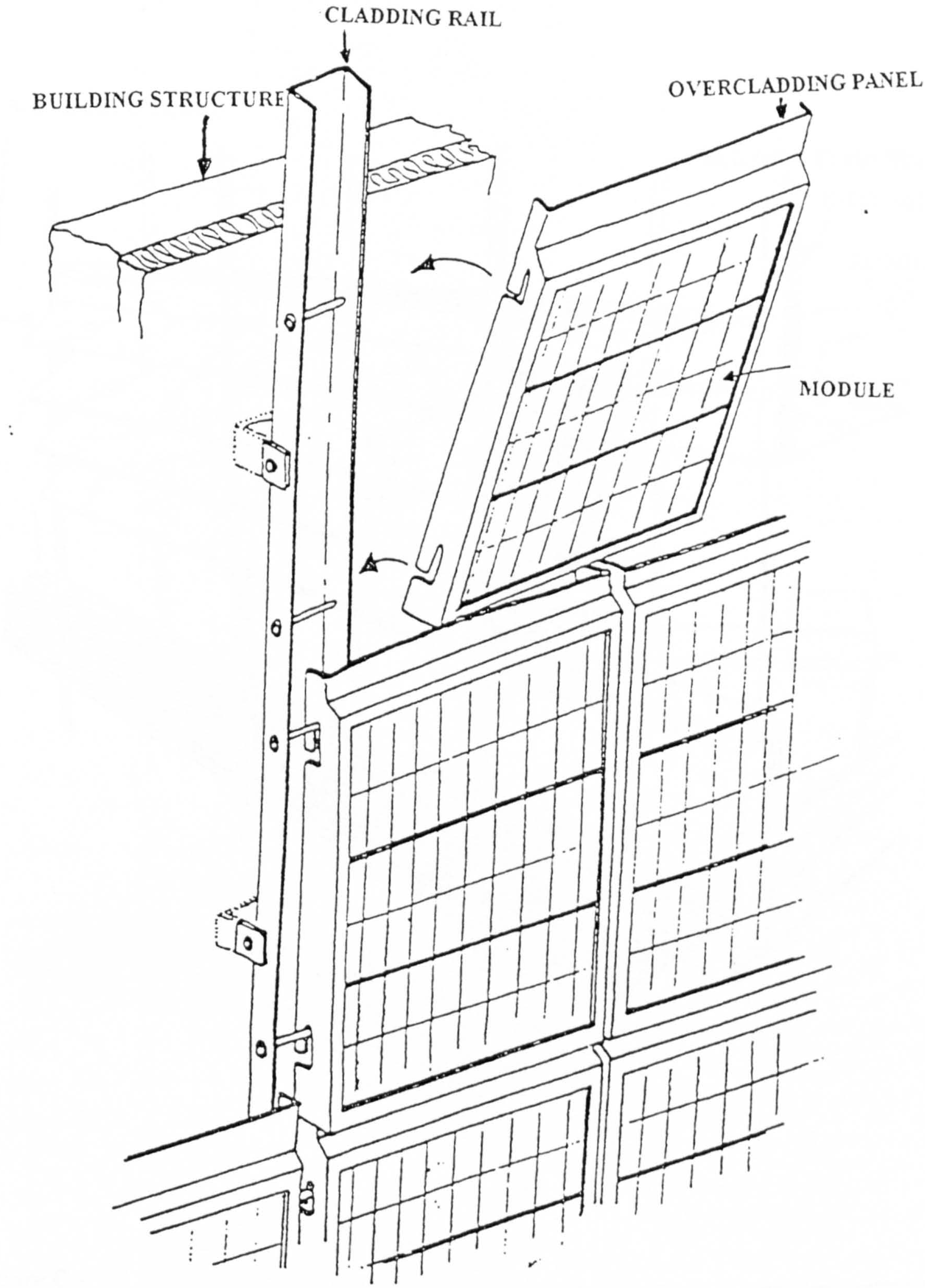


Figure C.3

Rainscreen overcladding

PV module integration

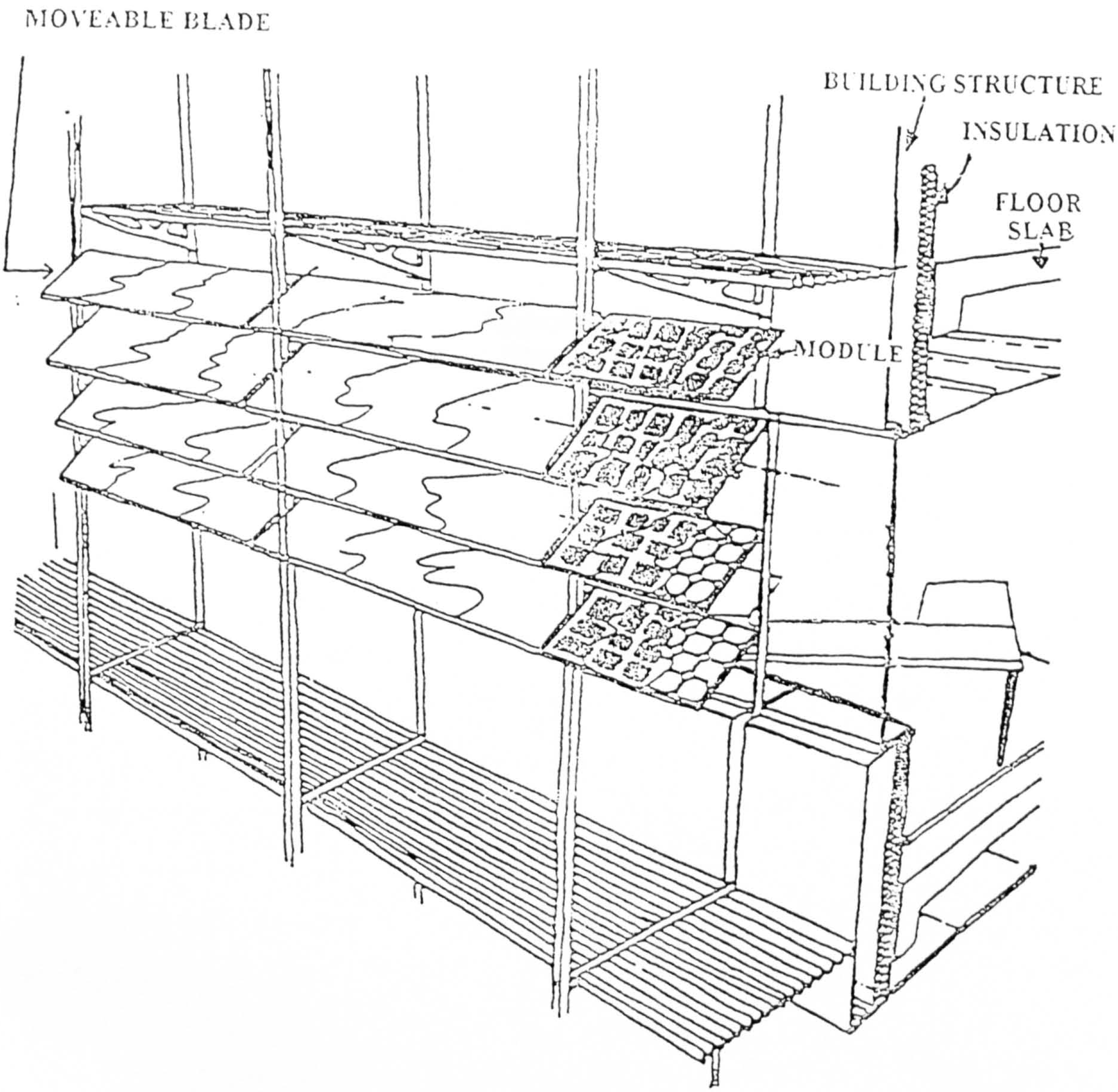


Figure C.4

Shading features - moveable blades

Appendix D
Glossary

GLOSSARY

Air mass

A measure of the distance that light travels through the earth's atmosphere

Altitude of the sun

This is the angle a direct ray from the sun makes with the horizontal at a particular place on the surface of the earth

Array

A collection of photovoltaic modules electrically wired together and mechanically installed in their working environment.(also series or isolation diode)

Autonomous system

A stand-alone PV system with no back-up generator, but which may have storage

Azimuth of the sun

This is the angle the horizontal component of a direct ray from the sun makes with the true north-sun axis

Balance of System(BOS)

The constituents of a photovoltaic system other than the array: switches, controls, meters, power conditioning equipment, supporting structure for the array and storage if present.

Blocking Diode

A device for preventing a reverse flow of current through photovoltaic modules

Building Envelope

The outside of a building that contains the interior space, including the roof: the skin or waterproof covering the structure.

Bypass Diode

A device placed in parallel with a photovoltaic module or a group of modules allowing a route for the current under conditions of shading and cell failure(also shunt diode)

Cladding

The external, weather protecting skin of a building

Cell Efficiency

The ratio of electrical energy produced by a photovoltaic cell (under full sun conditions) to the energy from sunlight falling upon the cell.

Charge Controller

A component that controls the flow of current to and from the battery subsystem to protect the batteries from overcharge and overdischarge. The charge controller may also monitor system performance and provide system protection.

Curtain Wall

The non-load-bearing wall placed as weather proof membrane round a structure, and usually made of glass or metal

DC to DC Converter

An electronic circuit, usually part of the maximum power point tracker, which converts a DC voltage, for instance a PV module voltage, to a higher level, for instance a load voltage.

Declination

This is the angular displacement of the sun from the plane of the earth's equator and varies from +23.5° and -23.5°

Design tilt

The tilt of the array at which the design and sizing calculations are made. Often the design tilt is optimised for energy output under prescribed conditions.

Diffuse radiation

Solar radiation that is received indirectly as a result of scattering due to clouds, fog, haze, dust or other substances in the atmosphere.

Direct Radiation

Light that has travelled in a straight path from the sun (also beam radiation)

Fill factor

The ratio of maximum power to the product open-circuit voltage and short-circuit current. It determines the squareness of the I-V curve shape

Flat-plate array

A photovoltaic array in which the incident solar radiation strikes a flat surface and no concentration of sunlight is involved.

Grid-connected

An energy producing system connected to the utility grid(also called utility interactive)

Grounding

Connection to a large conducting body, such as the earth, which is used as a common return for an electrical circuit and as an arbitrary zero potential.

Hot Spot Effect

An phenomenon whereby a partially or completely shaded cell becomes passive and the voltage from the remaining cells in series with it forces the reverse current through it and reverse biases it at a voltage which is the sum of the voltages of the other cells at open-circuit, with the effect that if the voltage is high enough, the cell goes into reverse-bias breakdown, heats up and fail by becoming either short-circuited or open-circuited.

Hybrid System

A power system consisting of two or more power generating subsystems, for example a wind-turbine and photovoltaic system combination

Inverter

A power converter which transforms DC voltage and current of the PV generator into single phase or multiphase AC voltage and current.

Insolation

The amount of sunlight reaching an area, usually measured in watts per square metre per day.

Junction box

A protective enclosure into which wires or cables are led and connected .

Load

Electrical power being drawn by anything in an electric circuit, which may vary greatly with time of day or time of year.

Line-Commutated Inverter

An inverter that is tied into a power grid or line, such that the commutation is controlled by the power line, and the system cannot feed power into the line if there is a failure in the power network.

Maximum Power Current(I_{mp})

The corresponding current for the maximum power point on I-V curve

Maximum Power Point(P_{max})

Air mass

A measure of the distance that light travels through the earth's atmosphere

Array

A collection of photovoltaic modules electrically wired together and mechanically installed in their working environment.(also series or isolation diode)

Autonomous system

A stand-alone PV system with no back-up generator, but which may have storage

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The constituents of a photovoltaic system other than the array: switches, controls, meters, power conditioning equipment, supporting structure for the array and storage if present.

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A device for preventing a reverse flow of current through photovoltaic modules

Building Envelope

The outside of a building that contains the interior space, including the roof: the skin or waterproof covering the structure.

Bypass Diode

A device placed in parallel with a photovoltaic module or a group of modules allowing a route for the current under conditions of shading and cell failure(also shunt diode)

Cladding

The external, weather protecting skin of a building

Cell Efficiency

The ratio of electrical energy produced by a photovoltaic cell (under full sun conditions) to the energy from sunlight falling upon the cell.

Charge Controller

A component that controls the flow of current to and from the battery subsystem to protect the batteries from overcharge and overdischarge. The charge controller may also monitor system performance and provide system protection.

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The non-load-bearing wall placed as weather proof membrane round a structure, and usually made of glass or metal

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An electronic circuit, usually part of the maximum power point tracker, which converts a DC voltage, for instance a PV module voltage, to a higher level, for instance a load voltage.

Design tilt

The tilt of the array at which the design and sizing calculations are made. Often the design tilt is optimised for energy output under prescribed conditions.

Diffuse radiation

Solar radiation that is received indirectly as a result of scattering due to clouds, fog, haze, dust or other substances in the atmosphere.

Direct Radiation

Light that has travelled in a straight path from the sun (also beam radiation)

Fill factor

The ratio of maximum power to the product open-circuit voltage and short-circuit current. It determines the squareness of the I-V curve shape

Flat-plate array

A photovoltaic array in which the incident solar radiation strikes a flat surface and no concentration of sunlight is involved.

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An energy producing system connected to the utility grid(also called utility interactive)

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Connection to a large conducting body, such as the earth, which is used as a common return for an electrical circuit and as an arbitrary zero potential.

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A power converter which transforms DC voltage and current of the PV generator into single phase or multiphase AC voltage and current.

Insolation

The amount of sunlight reaching an area, usually measured in watts per square metre per day.

Junction box

A protective enclosure into which wires or cables are led and connected .

Load

Electrical power being drawn by anything in an electric circuit, which may vary greatly with time of day or time of year.

Line-Commutated Inverter

An inverter that is tied into a power grid or line, such that the commutation is controlled by the power line, and the system cannot feed power into the line if there is a failure in the power network.

Maximum Power Current(I_{mp})

The corresponding current for the maximum power point on I-V curve

Maximum Power Point(P_{max})

The desired operating point on an I-V curve where the product of the current and voltage(power) is maximised.

Maximum Power Point Tracker(MPPT)

Means of a power conditioning unit that automatically operates the PV generator at its maximum power point under all conditions

Maximum power voltage(V_{mp})

The corresponding voltage for the maximum power point on the I-V curve

Module

A number of photovoltaic cells electrically wired together, usually in a sealed unit of convenient size for handling and assembling into panels and arrays

Mullion

A slender pier which forms the division between the lights of a window, a screen or an opening.

Mullion/Transom

A facade construction often used with curtain wall facades, and consists of vertical beams(mullions) and horizontal beams(transoms)

Nominal Operating Cell Temperature(NOCT)

The photovoltaic cell junction temperature corresponding to nominal operating conditions in a standard reference environment of $1kW/m^2$ irradiance, 20°C ambient air temperature, 1m/s wind, and electricity open-circuit

Open-circuit voltage(V_{oc})

The voltage output of an illuminated photovoltaic device when no current is flowing through the circuit, which is also the maximum possible voltage

Overhang

The projection of a storey or any part of the building attached to the wall of the building

Panel

A number of modules wired together which in turn, can be wired to other panels to form an array.

Parallel Connected

A method of connection in which positive terminals are connected together and negative terminals are connected together, giving the sum of currents as the total current, but the voltage remaining the same

Peak sun hours

The equivalent number of hours at peak sun conditions ($1kW/m^2$) that produces the same total insolation a the actual sun conditions

Peak watts(W_P)

The amount of power a photovoltaic cell or module produces at nominal irradiation conditions (STC)

Photovoltaic Cell

The basic device that converts light into dc electricity ; the building block of PV modules

Photovoltaic String

A series connection of individual modules or equal groups of several paralleled modules

Photovoltaic System

A complete set of components for converting solar radiation into electricity by the photovoltaic process, including the array and the balance of system.

Polycrystalline silicon

Silicon that has solidified at such a rate that many small crystals (crystallites) were formed, with the atoms within a single crystallite symmetrically arranged, whereas the crystallites are not ordered (also multicrystalline)

p-n junction

The junction formed at the interface between two differently doped layers of semiconductor material, one layer being doped with a positive-type dopant, the other with a negative-type dopant. An electric field is established at the p-n junction which which gives the direction to the flow of light-stimulated electrons.

Semiconductor

A substance with conducting properties intermediate between those of a conductor and an insulator. Its resistance increases with temperature, and energy sources such as light also have the same effect on it.

Series-Connected

A method of connection in which the positive terminal of one device is connected to the negative terminal of another. The voltage add and the current is limited to the least of any device in the string

Short-circuit current(I_{sc})

The current flowing freely from a photovoltaic cell through an external circuit that has no load or resistance; the maximum current possible under normal operating conditions.

Skylight

A frane containing glass or translucent/translucent material, set in a roof.

Solar Constant

The rate at which energy is received from the sun just outside the earth's atmosphere on a surface perpendicular to the sun's rays. It i approximated to be 1.36kW/m^2.

Standard Test Conditions(STC)

Test conditions in a standard reference environment of 1kW/m^2, 25°C solar cell temperature, and 1.5 air mass spectrum(AM 1.5)

Stand-off mounting

A technique for mounting a PV array on a slope roof that involves mounting the modules a short distance above the pitched roof and tilting them to the optimum angle.

Structural glazing

A system of retaining glass or other materials to the aluminium members of a curtain wall using silicon sealant. It uses no mechanical fasteners, and therefore have no profiles which cast shadows on the glazing surface.

Thick Cells

Conventional cells, such as crystalline silicon cells, which are typically 400 to 1700μm thick.

Thin-film Cells

Photovoltaic cells, made of many layers of photosensitive material less than 10μm thick, which are typically applied by a chemical vapour deposition process in the presence of an electric field.

Transom

A horizontal bar dividing a window or opening into two or more lights in height.

Voltage Regulator

A device that controls the operating voltage of a photovoltaic array

Watt

A measure of electrical power. It is produced when one amp of current flows at a potential 1 volt